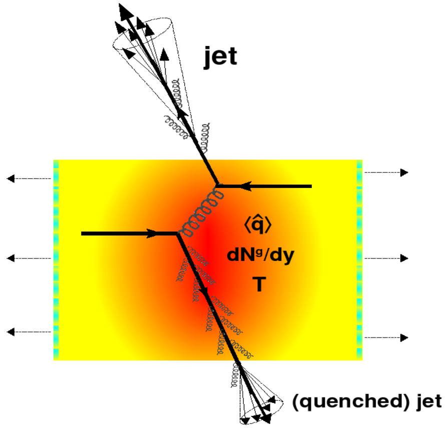
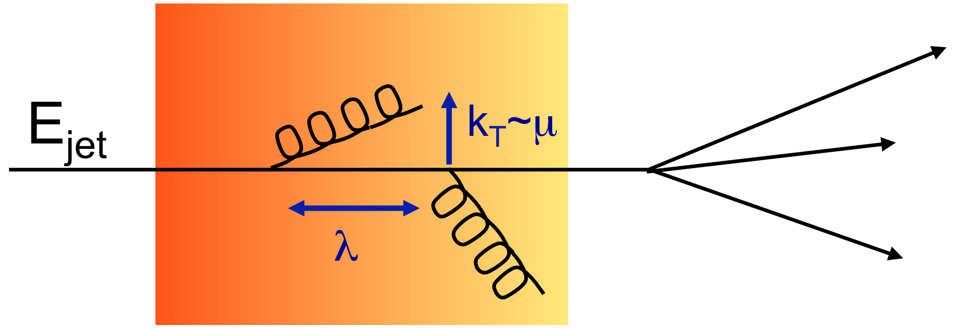
Profiting from countless arguments and work with James Mulligan & Peter Jacobs



Jets in Heavy Ion Collisions: Open Questions and New Ideas

Please note that this talk is **not a review of the results in heavy-ion collisions**. We would like to hear from you on **the open questions and new ideas which could be performed by the LHC experiments (ALICE, ATLAS, CMS, and LHCb) and STAR / sPHENIX at RHIC**. When possible, please make connections to the general QCD program in the HEP community.

One-line reminder: goal is to learn physical properties of QGP through jet modifications (including microscopic structure)



Note: likely jet is a shower – not a line even in medium…

Longitudinal modification

- out-of-cone: energy lost, loss of yield, di-jet energy imbalance
- in-cone: softening/hardening of fragmentation

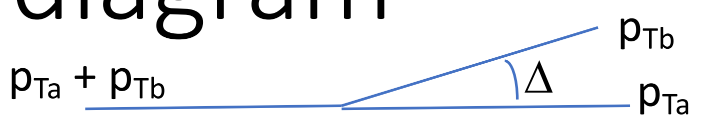
Transverse modification

- out-of-cone: increase acoplanarity kT
- in-cone: broadening of jet-profile

Executive Summary

- Need for precision measurements on jet substructure modifications that correlate the energy-loss and substructure modifications
  - Measure larger R – more sensitivity to medium resolution (experimentally difficult but ‘new’ methods may be available)
  - High **and low-pT** matters – dynamic range of the in-medium “radiators"
  - High precision Z-jet, gamma-jet, heavy-quark jets (at low pT) – towards q/g discrimination
  - New development: Inclusive measurements (all splittings – complete Lund Diagram) instead of groomed -> ensemble basis analyses (subtract the mis-tagged splittings)
  - Expand on novel Machine Learning techniques – suppress / improve corrections (background)
- High multiplicity collisions are not lower multiplicity PbPb collisions
  - HM pp as a good reference for (likely only) N^xLO corrections to in-medium effects (within jets) in AA => good lesson for what high multiplicity pp collisions are
- Looking forward to the LHC Run-3&4 and RHIC sPHENIX era
- Beyond that? Yoctosecond structure of QGP with top quarks – HE-LHC (low signal for HL-LHC) (https://doi.org/10.1016/j.nuclphysa.2018.11.014)

Jet Lund diagram



$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

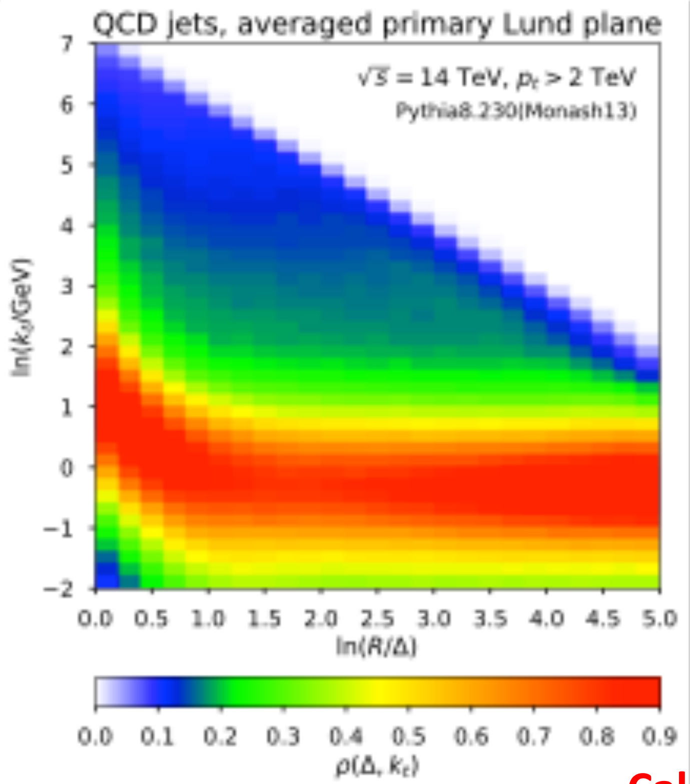
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

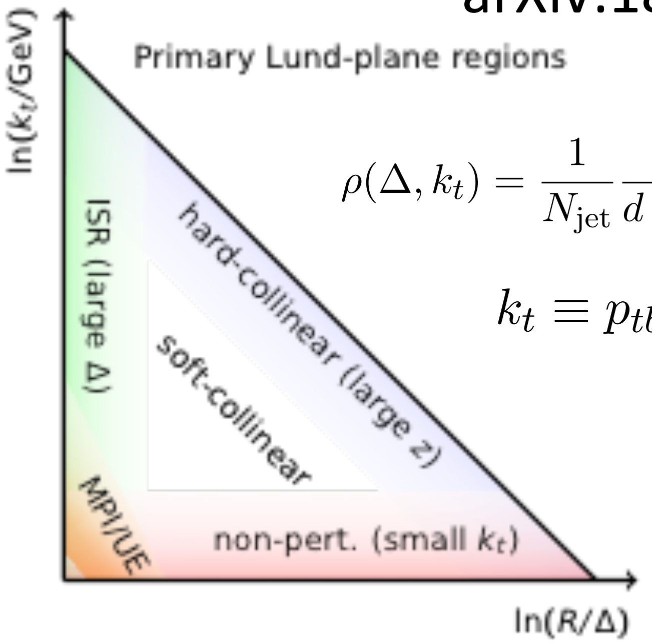
Lund diagrams, a theoretical representation of the phase space within jets, have long been used in discussing parton showers and resummations. We point out that they can be created for individual jets through repeated Cambridge/Aachen declustering, providing a powerful visual representation of the radiation within any given jet.

arXiv:1807.04758

Study in HI collisions

Select splittings (remove soft large angle radiation)
$\Rightarrow$ groom jets





$$\rho(\Delta, k_t) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln k_t\, d\ln 1/\Delta}$$

$$k_t \equiv p_{tb}\Delta_{ab},$$

To leading order in perturbative QCD and for $\Delta \ll 1$, one expects for a quark initiated jet

Calculable(!)

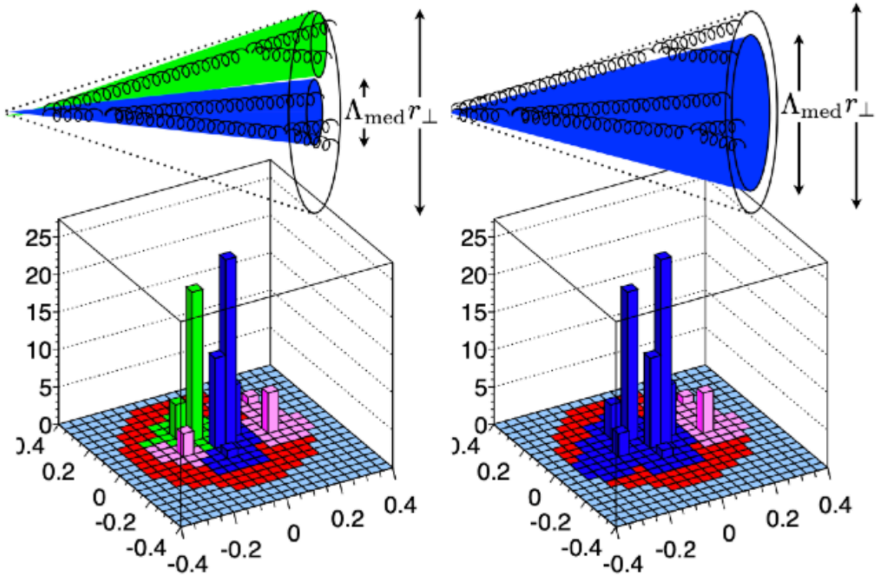
$$\rho \simeq \frac{\alpha_s(k_t)C_F}{\pi}\bar{z}\left(p_{gq}(\bar{z}) + p_{gq}(1-\bar{z})\right), \quad \bar{z} = \frac{k_t}{p_{t,\text{jet}}\Delta}$$

On current experimental data - Jet measurements in AA
A 5 minute summary

- Inclusive jets in AA suppressed as compared to pp: suppression similar for low and high jet pT
- Z-jet, gamma-jet, hadron-jet: e-loss ~10-15% of the jet energy; similar at RHIC and LHC
- Missing energy recovered at large angles
- FF modified – differently for inclusive jets as compared to photon tagged jets – still not conclusive (difference in quark vs glue e-loss?, ”surface bias” for inclusive jets?)
- No quark/gluon fraction modification at high-pT
- Jet radial moment and hadron-jet correlations – energy profile modified – narrower in AA (a la quark)
- Sub-jet structure:
  - Mass: small modification at large mass (small z_{cut}) – no modification in the jet core (SD z_{cut}>0.5 beta=1.5)
  - Fully corrected SD z_{cut}>0.2: z unmodified; small angles enhances; large angles depleted

Main idea: does medium resolve the shower & how?

=> Medium properties (microscopic picture?)



Jet quenching – an MC study towards new measurements…

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams - Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

https://arxiv.org/pdf/1812.06772.pdf

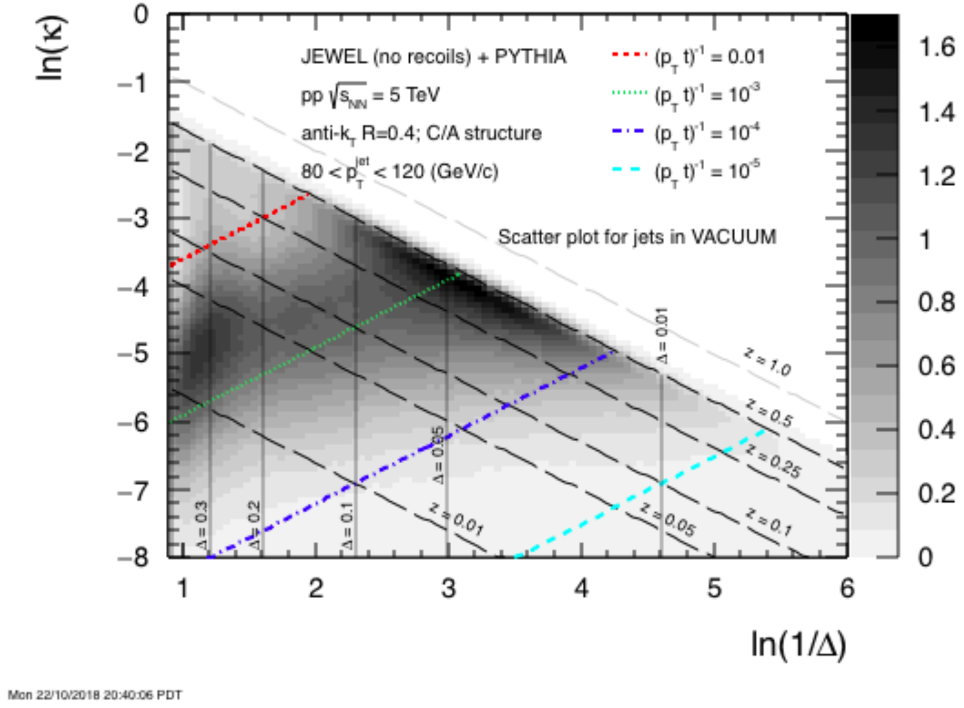
Jet Lund diagram

$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

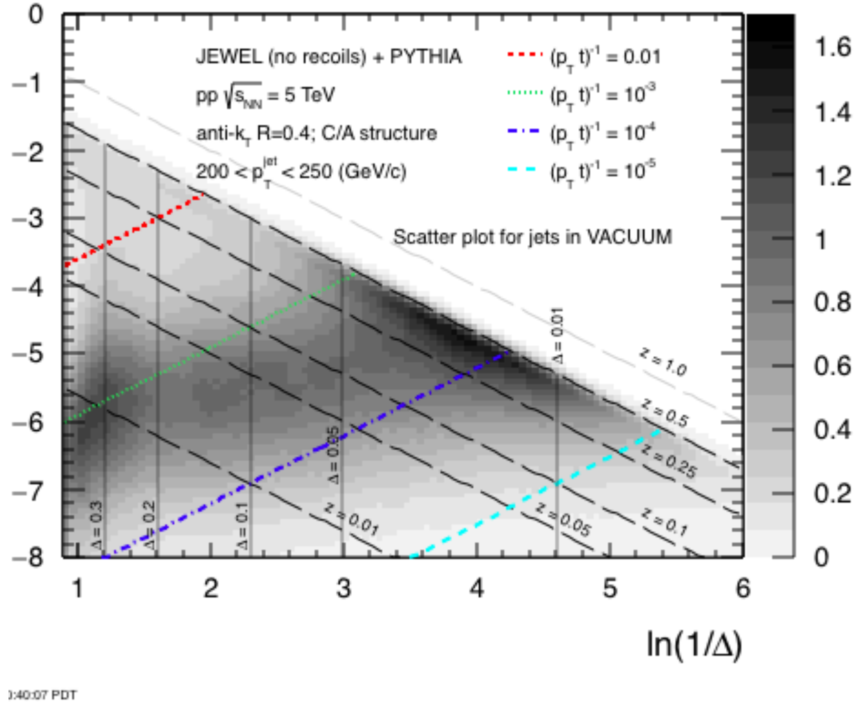
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

JEWEL + PYTHIA (RECOIL=OFF)
10% most central PbPb at 5 TeV
VACUUM

80-120 GeV/c



200-250 GeV/c



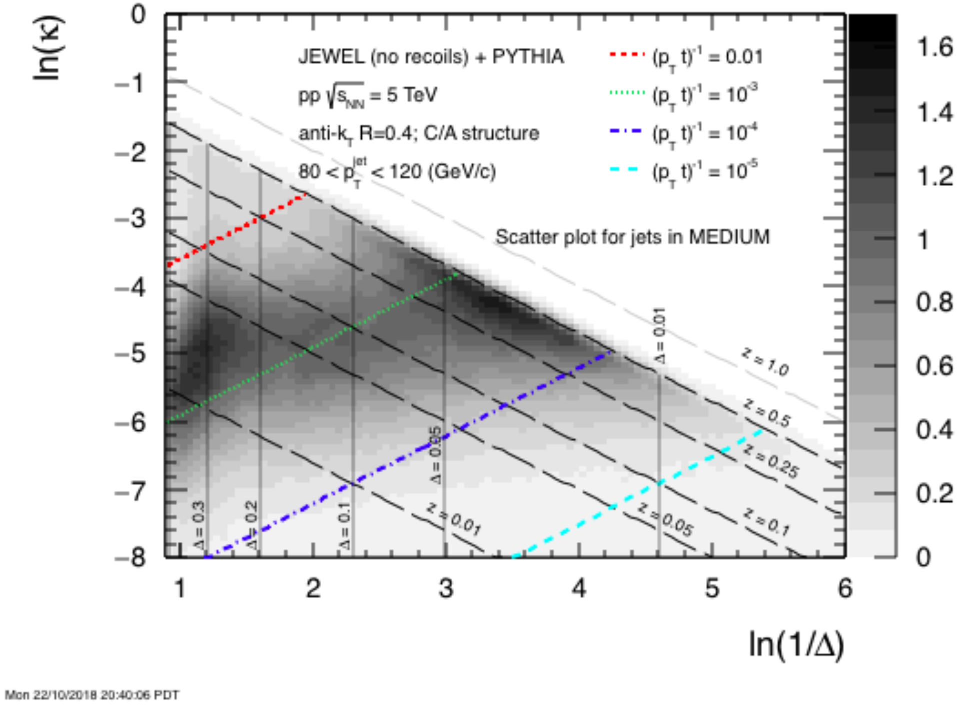
Jet Lund diagram

$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

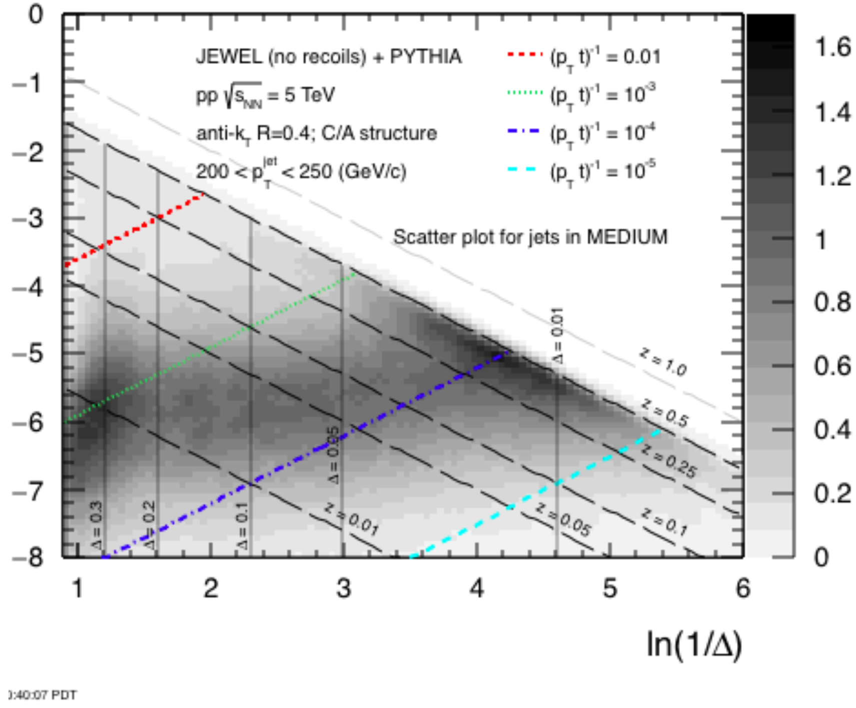
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

JEWEL + PYTHIA (RECOIL=OFF)
10% most central PbPb at 5 TeV
MEDIUM

80-120 GeV/c



200-250 GeV/c



JEWEL: https://arxiv.org/abs/1311.0048 MC simulating QCD jet evolution in heavy-ion collisions. It treats the interplay of QCD radiation and re-scattering in a medium with fully microscopic dynamics in a consistent perturbative framework

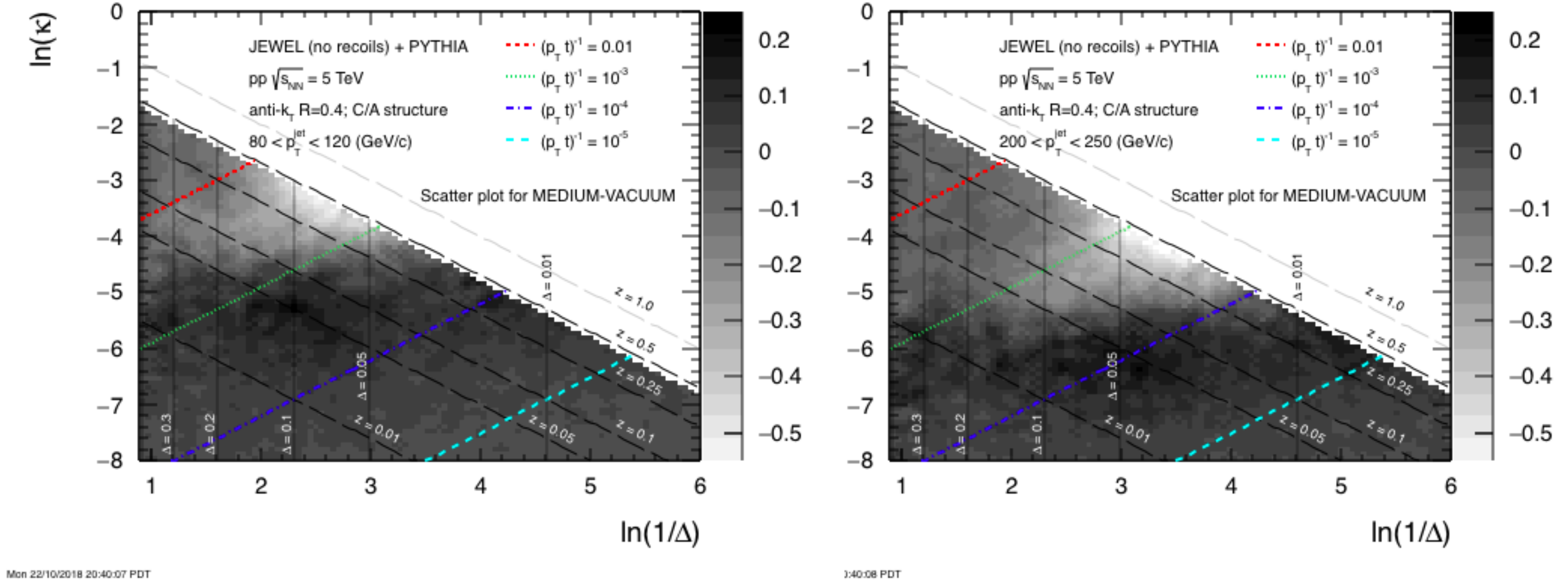
Jet Lund diagram

$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

JEWEL + PYTHIA (RECOIL=OFF)
10% most central PbPb at 5 TeV
MEDIUM - VACUUM

80-120 GeV/c　　200-250 GeV/c



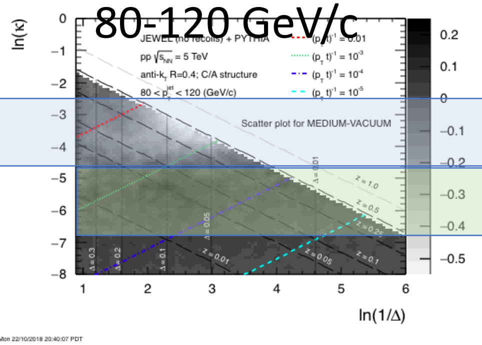
JEWEL: https://arxiv.org/abs/1311.0048 MC simulating QCD jet evolution in heavy-ion collisions. It treats the interplay of QCD radiation and re-scattering in a medium with fully microscopic dynamics in a consistent perturbative framework

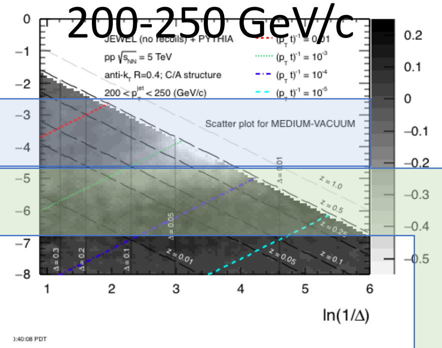
Jet Lund diagram

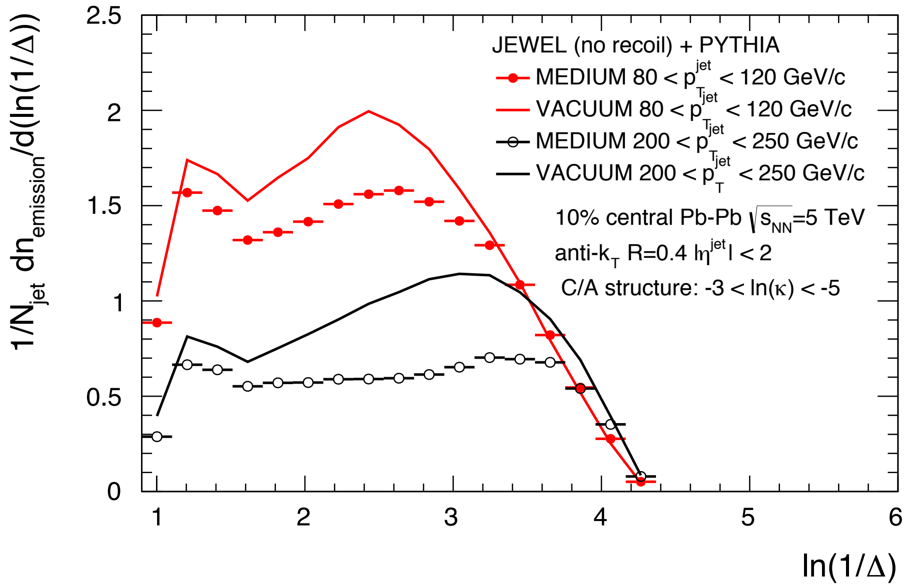
$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

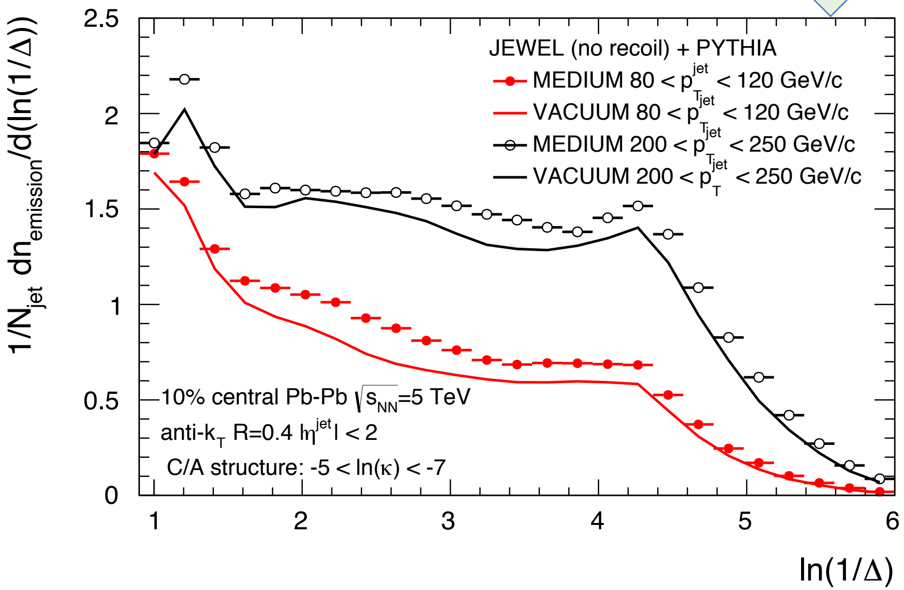
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

JEWEL + PYTHIA (RECOIL=OFF)
10% most central PbPb at 5 TeV
MEDIUM - VACUUM





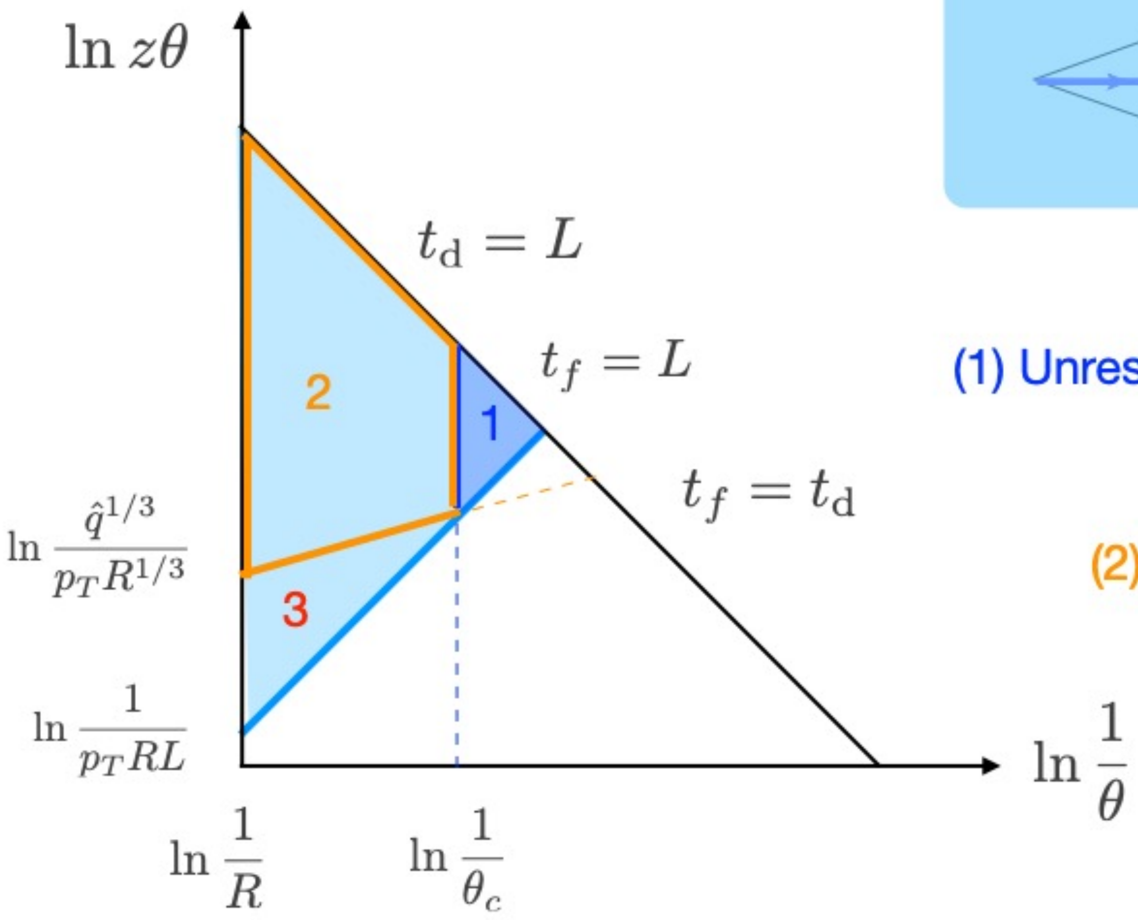


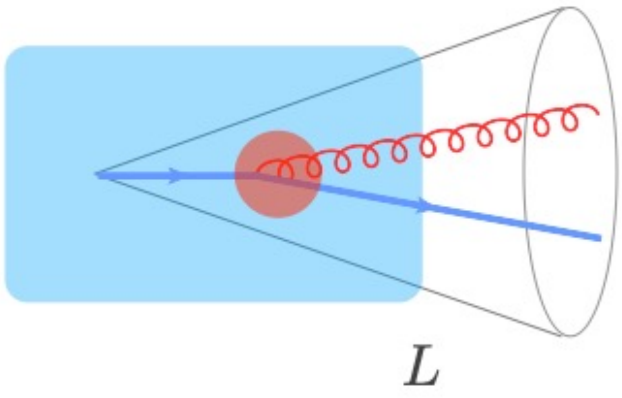


Lund in service of mapping out in-medium modifications

[Andrews et al (2018)]

formation time: $t_f = (\omega\theta^2)^{-1}$





(1) Unresolved in medium splitting

$t_{\mathrm{d}} > L$

(2) Resolved vacuum splitting inside the medium

$t_f < t_{\mathrm{d}} < L$

(3) Medium-induced radiation

$t_{\mathrm{d}} < t_f < L$

Slide by Yacine Mehtar-Tani

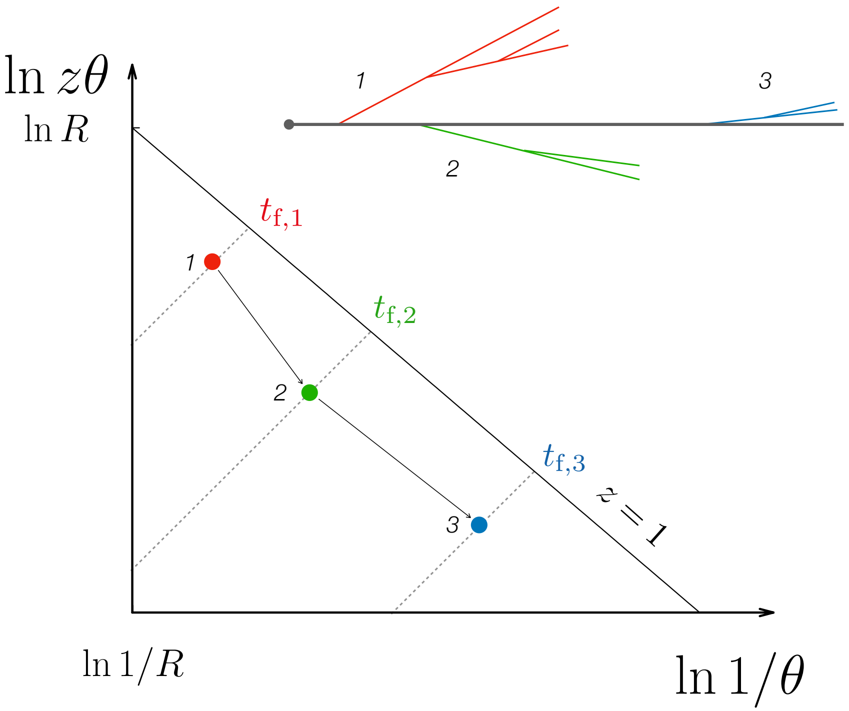
Lund in service of mapping out in-medium modifications

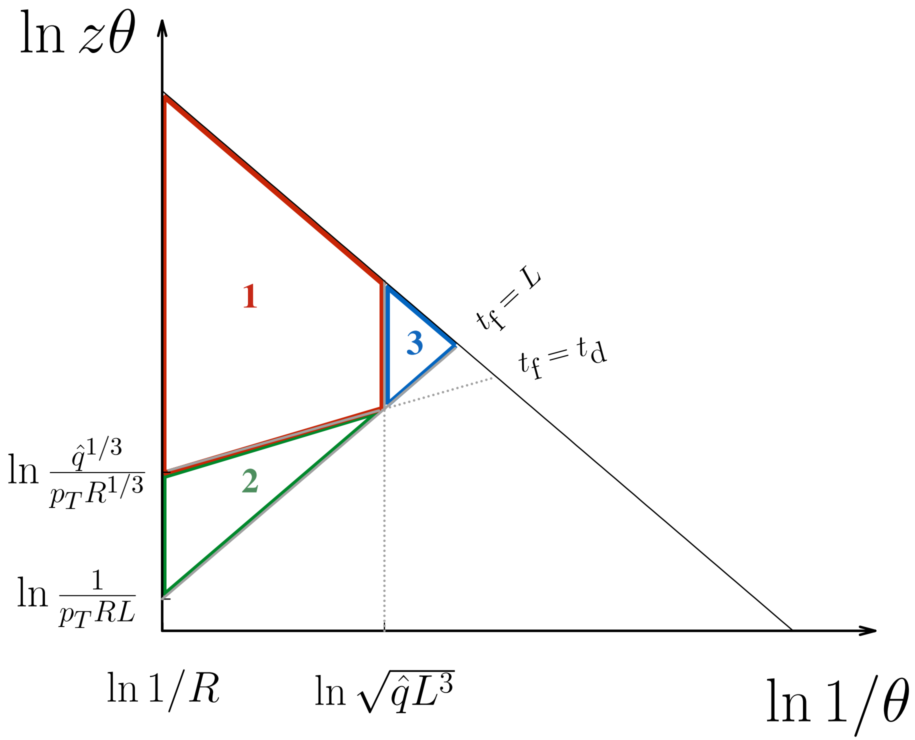
the detector. The characteristic time-scale of the splitting is usually referred to as the *formation time*, and is related to the finite energy resolution, $t_{\rm f} \sim \Delta E^{-1}$. It is explicitly given by

$$t_{\rm f} = \frac{2z(1-z)p_{\rm T}}{k_{\rm T}^2} = \frac{2p_{\rm T}}{M^2}\,, \tag{2}$$

where $k_{\rm T} = z(1-z)p_{\rm T}\theta$ is the (relative) transverse momentum of the dipole in the small angle limit. This formula can easily be understood as the time-scale for decaying in the rest frame of the parent times its boost factor $\sim (1/M) \times (p_{\rm T}/M)$.

https://arxiv.org/pdf/1808.03689.pdf





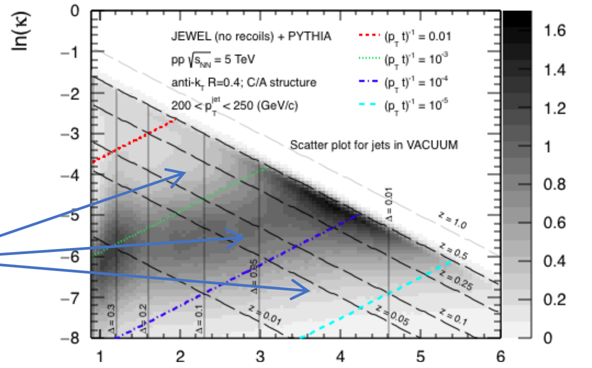
$$\ln z\theta = \ln \frac{1}{\theta} + \ln \frac{1}{p_{\rm T} t}\,,$$

Jet Lund diagram slicing through time

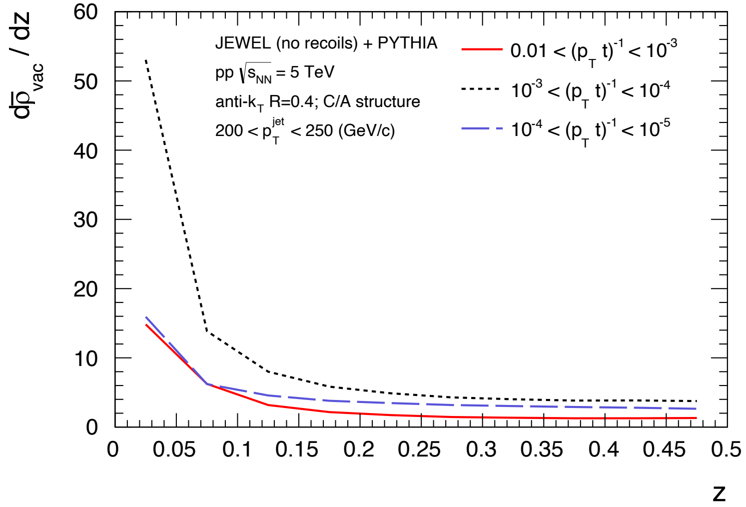
$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

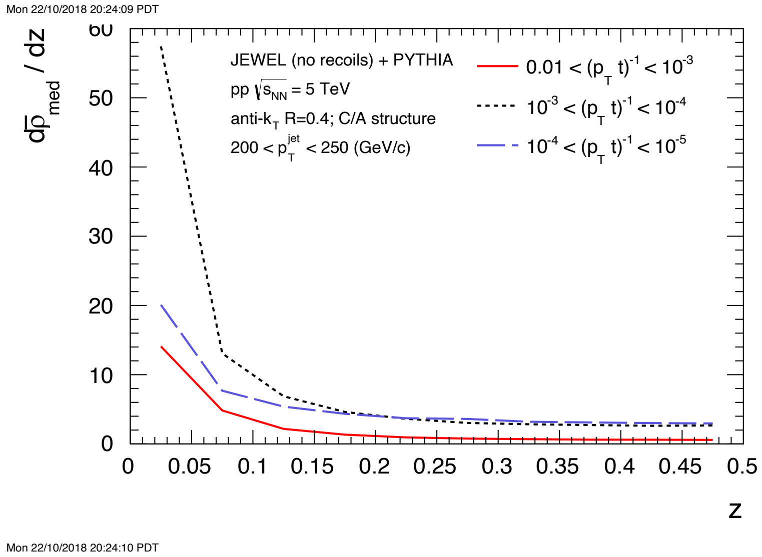
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\rm jet}}\frac{dn_{\rm emission}}{d\ln\kappa\ d\ln 1/\Delta}$$

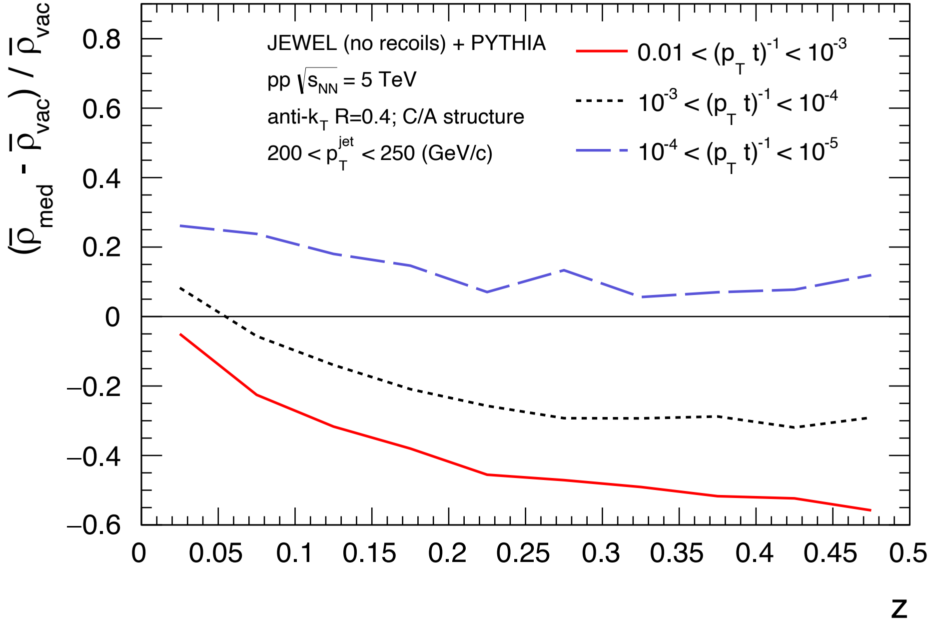
80 – 120 GeV/c



Slicing along $1/(p_T \times t)$ and projecting along z



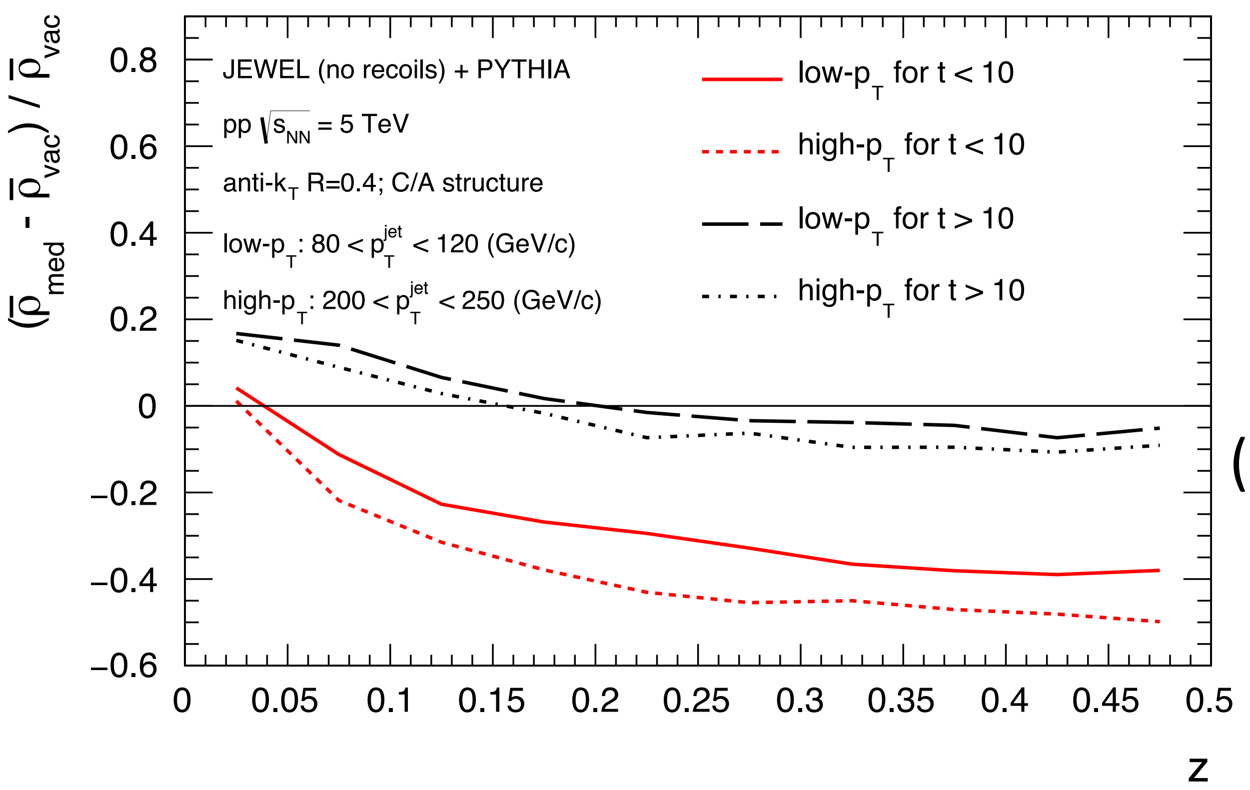




Jet Lund diagram slicing through time

$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\rm jet}}\frac{dn_{\rm emission}}{d\ln\kappa\ d\ln 1/\Delta}$$



Low- with high-p_T for the similar t

⇔

similar suppression (scaling factor for p_T x t roughly 80/200)

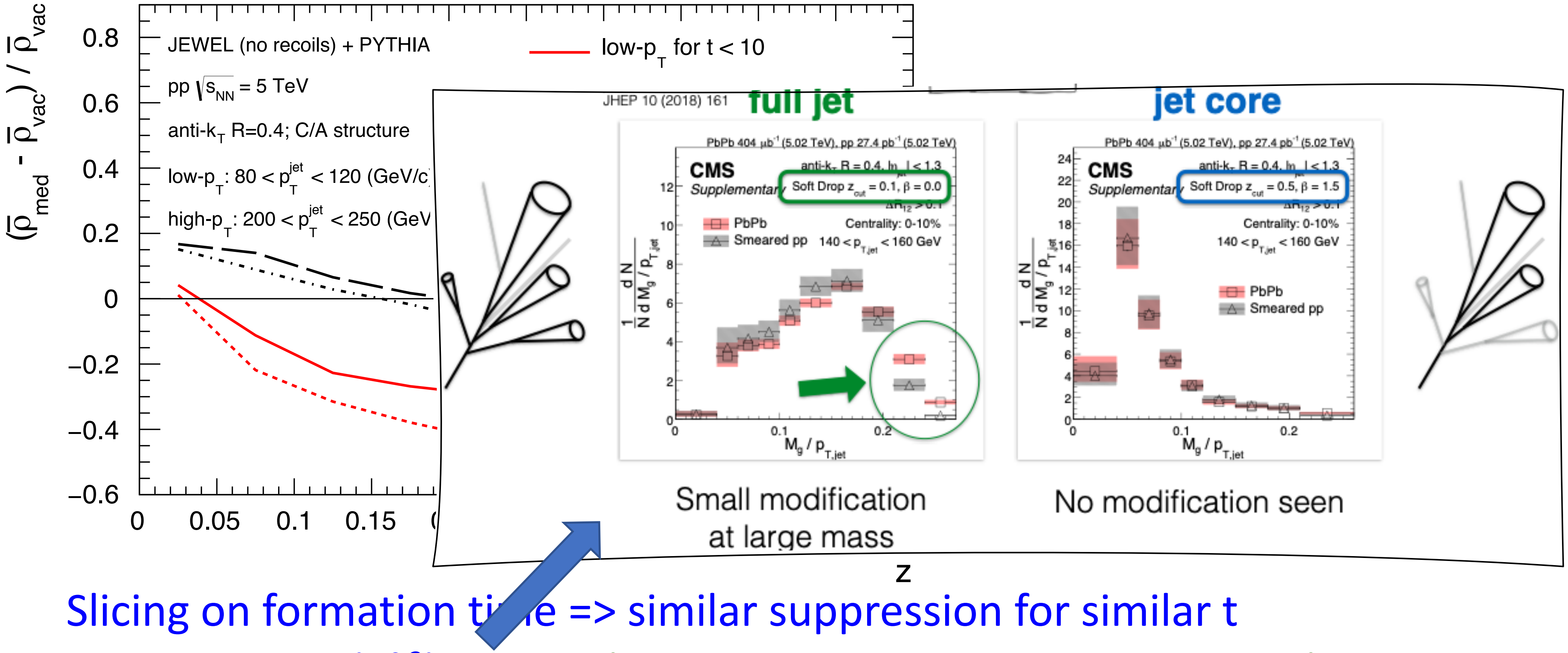
Slicing on formation time => similar suppression for similar t

Explore: Mass ($z\theta^2$) slicing?

Jet Lund diagram slicing through time

$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\mathrm{jet}}}\frac{dn_{\mathrm{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

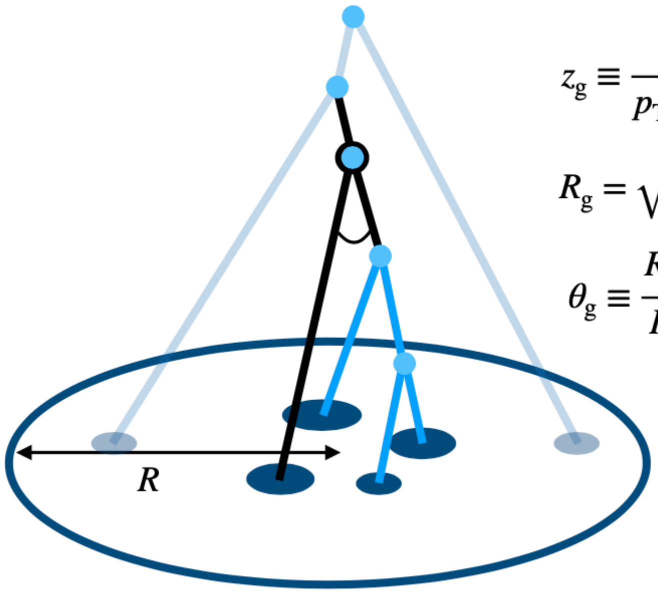


Slicing on formation time => similar suppression for similar t

Explore: Mass ($z\theta^2$) slicing? (some of that already started – CMS)

Jet substructure – present and outlook

- Current / measured:
  - Soft drop, mass (groomed and ungroomed), girth
  - Broad strokes conclusion: medium modifies internal jet structure – "narrowing" of energy jet profile and (new) angular structure of hard splittings
- Future directions? – agenda for Today
  - **Substructure vs. E-loss - Z-jet, gamma-jet for example**
  - **Measure large R jets; push for low-jet pT**
  - **Explore different groomers and grooming algorithms**
  - Different substructure approaches – re-clustering:
    - Fragmentation into subjets – inclusive vs. leading subjets
    - Axis correlations (std. jet axis vs. WTA) – sensitivity to
  - Jet angularities (mass, girth, limits)



$$z_g \equiv \frac{p_{\mathrm{T,subleading}}}{p_{\mathrm{T,leading}} + p_{\mathrm{T,subleading}}}$$

$$R_g = \sqrt{\Delta y^2 + \Delta \varphi^2}$$

$$\theta_g \equiv \frac{R_g}{R}$$

Graph by J. Mulligan

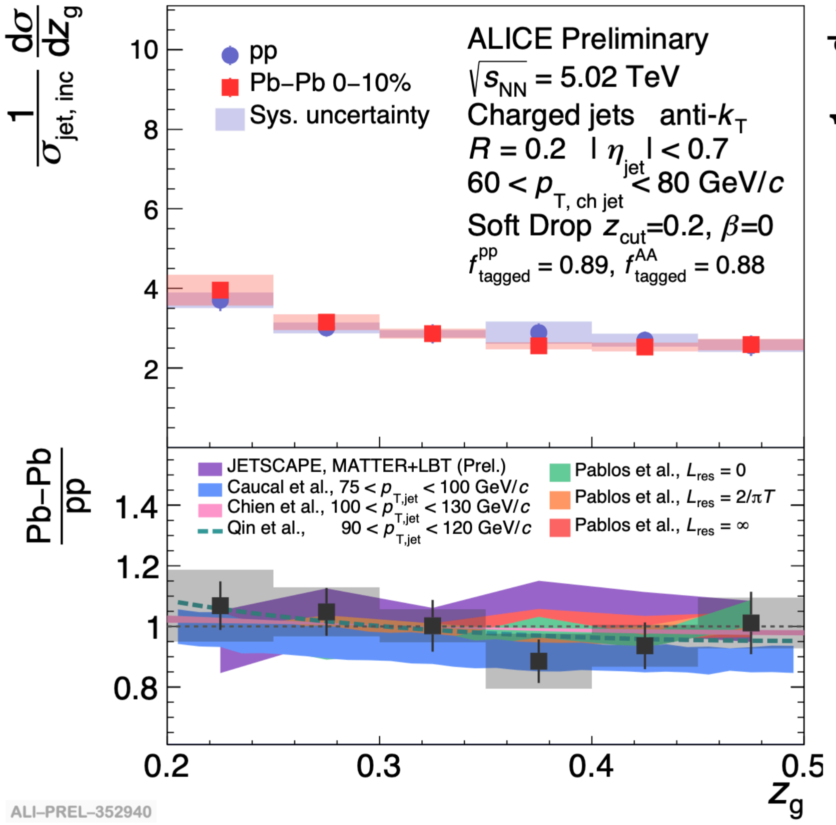
Soft Drop, Recursive SD, Iterative SD
https://arxiv.org/abs/hep-ph/9707323
https://arxiv.org/abs/hep-ph/9907280
https://arxiv.org/abs/1804.03657
https://arxiv.org/abs/1704.06266

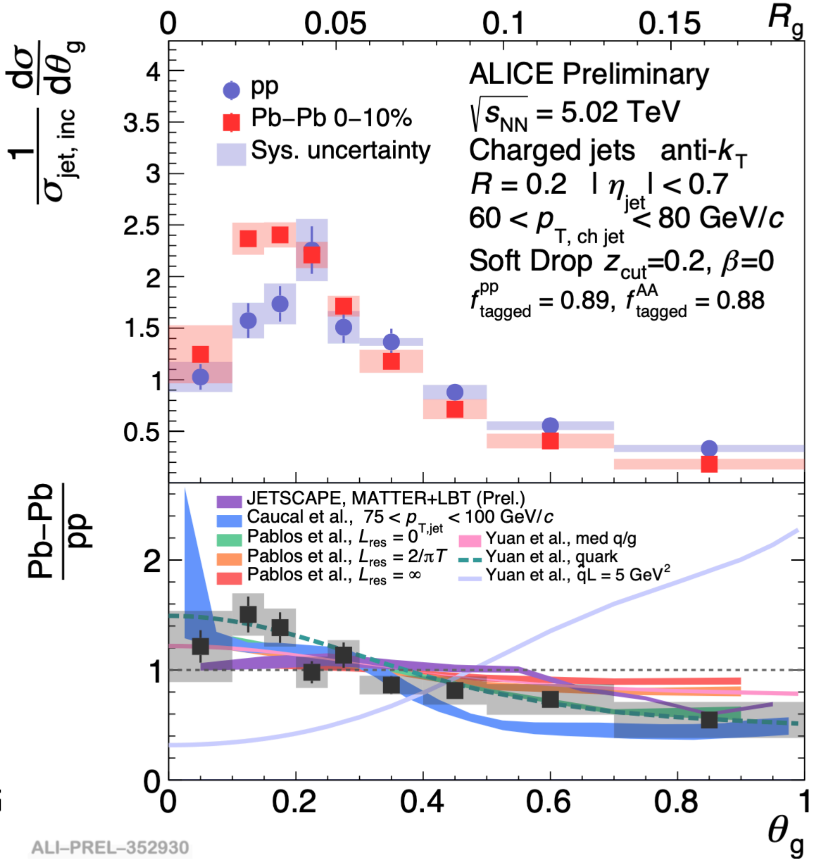
Let’s dissect a recent measurement

- ALICE measurement of groomed jet z and theta
  - Fully corrected –> no z_g modifications (!) but angular structure modified

No significant modification of z_g distribution

Modification of θ_g: Collimation / Narrowing



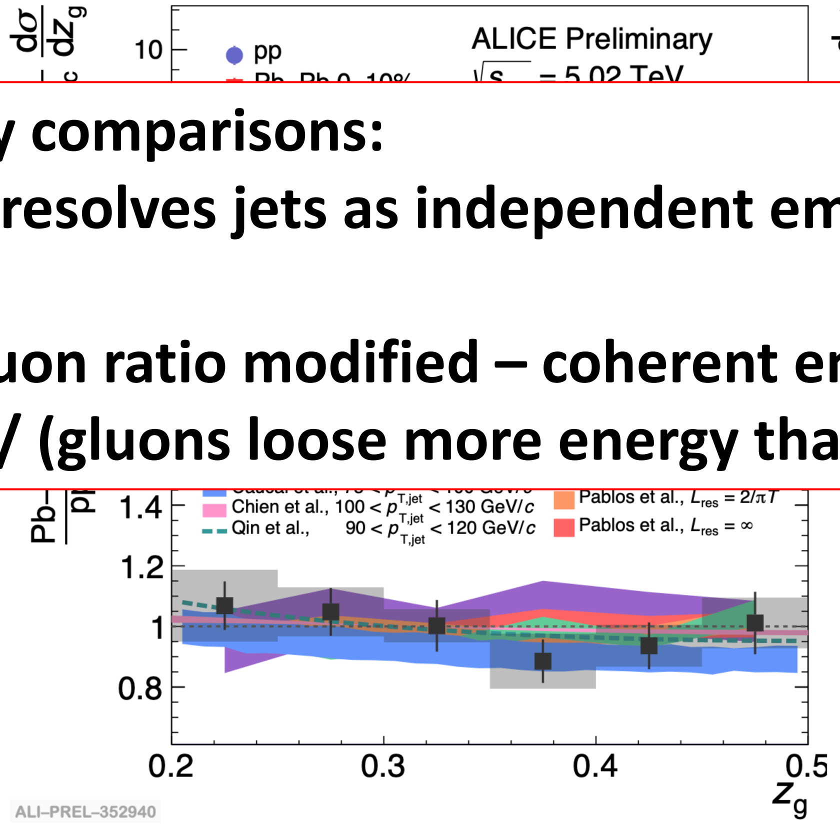


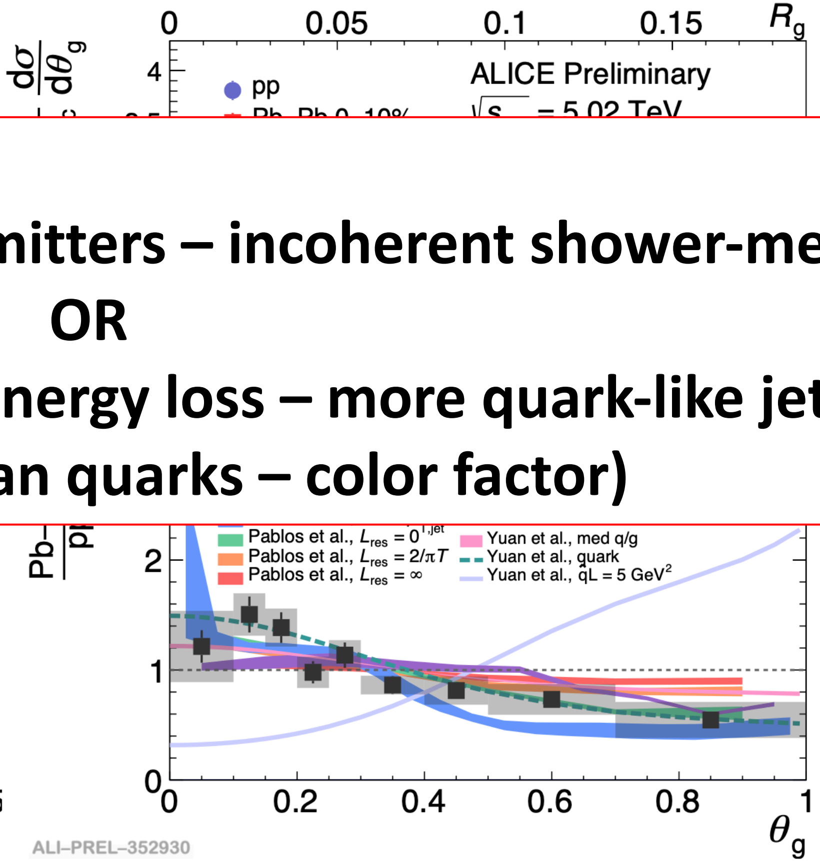
Let’s dissect a recent measurement

- ALICE measurement of groomed jet z and theta
    - Fully corrected – no z modifications (!) but angular structure modified

No significant modification of z_g distribution

Modification of θ_g: Collimation / Narrowing





From theory comparisons:

$\Rightarrow$ medium resolves jets as independent emitters – incoherent shower-medium interactions

OR

$\Rightarrow$ quark/gluon ratio modified – coherent energy loss – more quark-like jets emerging /or selected / (gluons loose more energy than quarks – color factor)

Quark vs. gluon jets vs. resolution of angular scale

Well known (but sometimes subtle points) – potential to leverage (with sufficient understanding) in AA collisions

$\Rightarrow$ Jet energy profile depends on energy – higher-E more collimated structure

  $\Rightarrow$ Are lower pT jets more likely to be resolved by the medium?

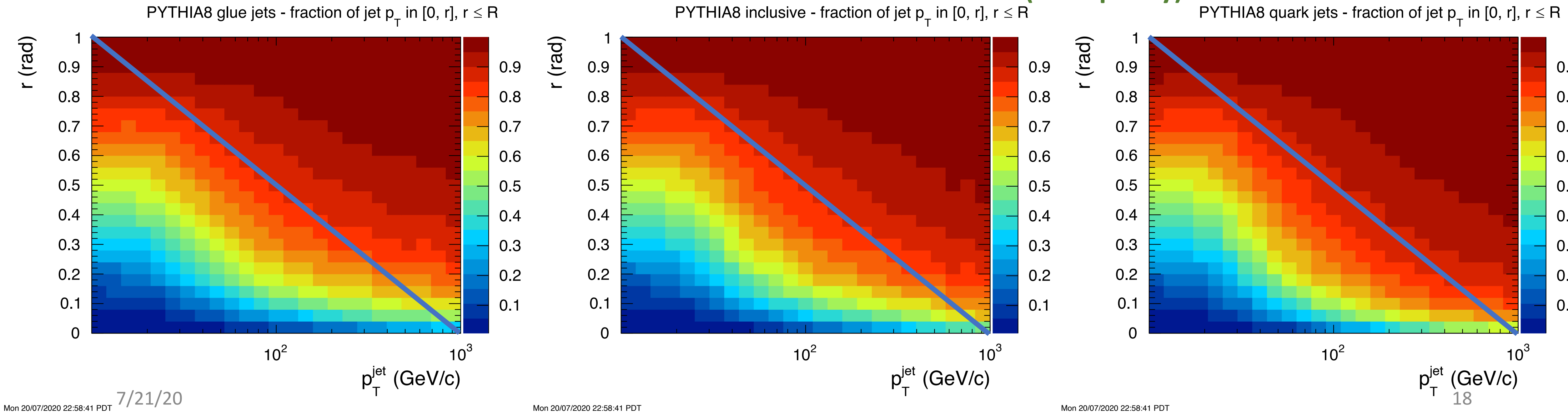
$\Rightarrow$ Jet energy profile depends on parton type – glue induced jets less collimated than quarks

  $\Rightarrow$ Do color factors – play a role – how strong? (showering dilutes the effect for incoherent interactions?)

$\Rightarrow$ Quark/gluon ration changes with jet pT

  $\Rightarrow$ Higher momentum gluon jets appear as quark jets after the in-medium energy loss (softer prongs removed from the jet)

Subtle differences but well *seen* in a number of observables (multiplicity) and ML

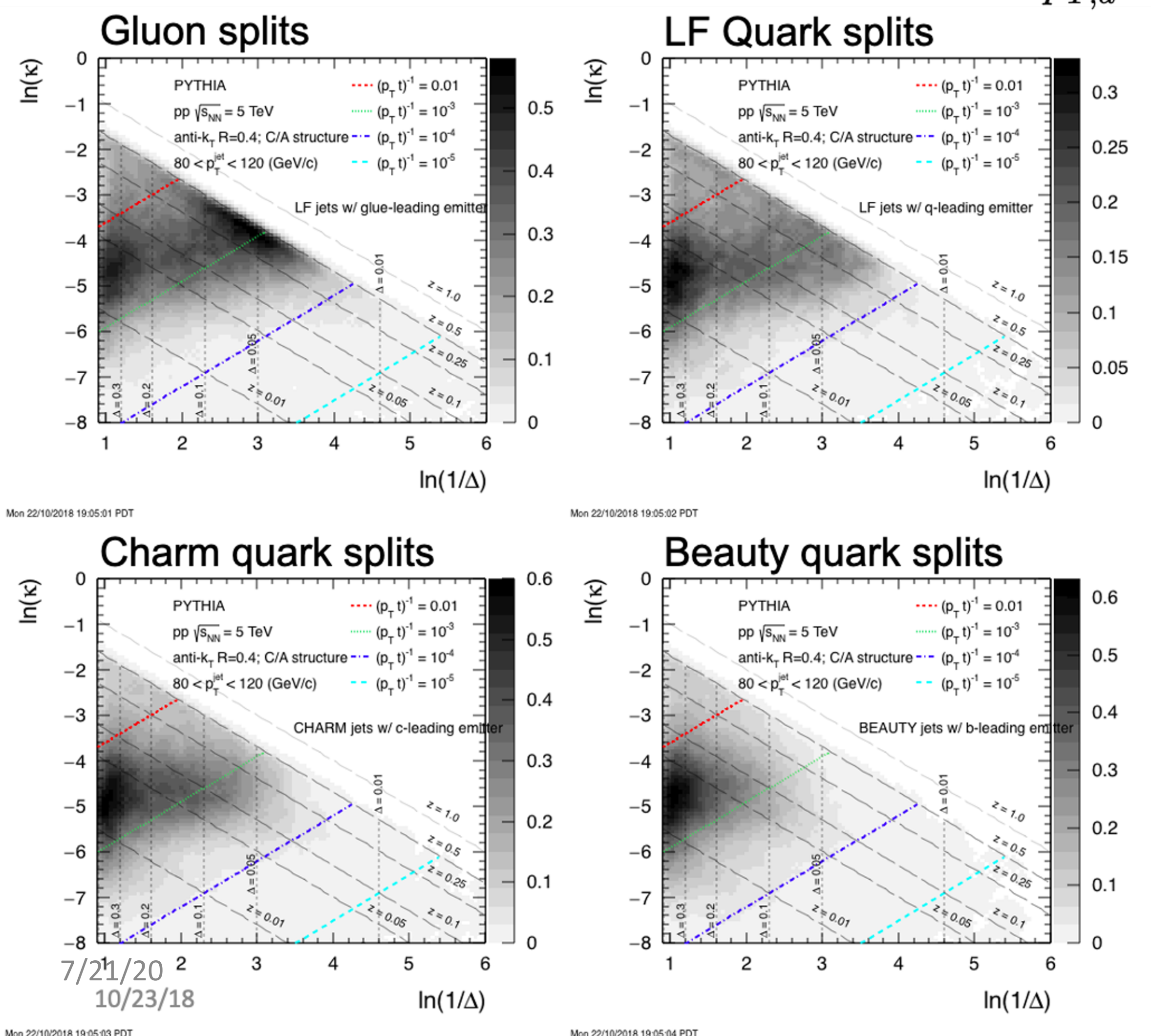


Quark vs. gluon jets vs. resolution of angular scale

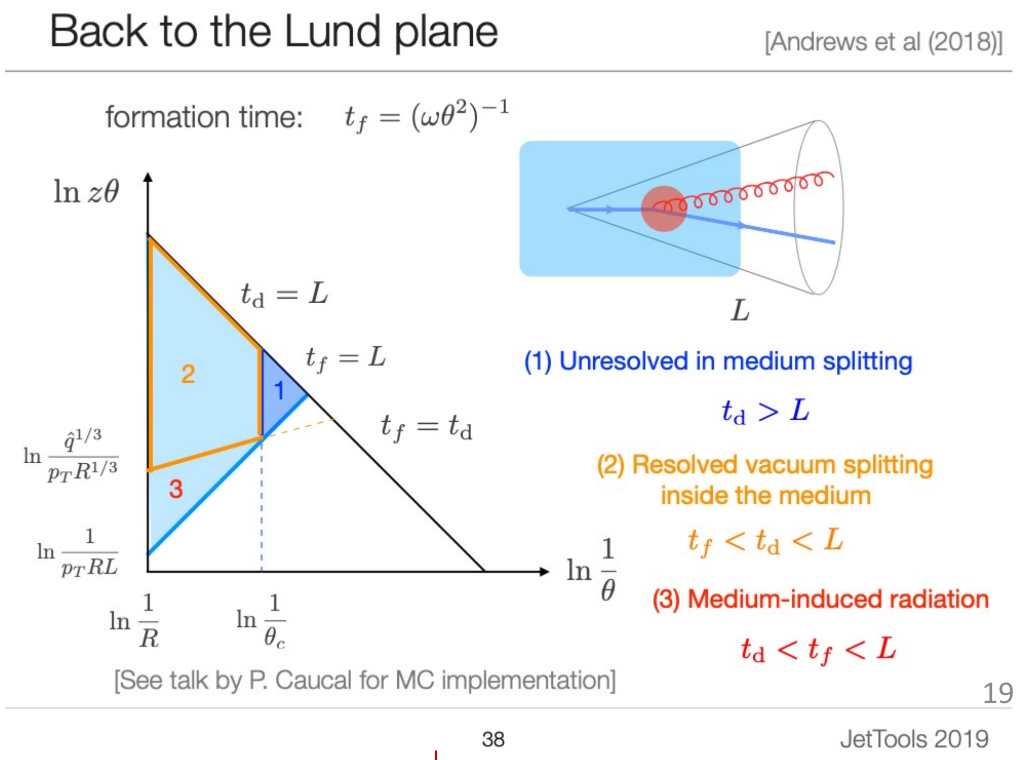
45

$$\bar{\rho}(\Delta, \kappa) = \frac{1}{N_{\mathrm{jet}}} \frac{dn_{\mathrm{emission}}}{d\ln\kappa \; d\ln 1/\Delta}$$

$$p_{T,a} > p_{T,b}, \;\; \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}} \Delta_{ab}$$

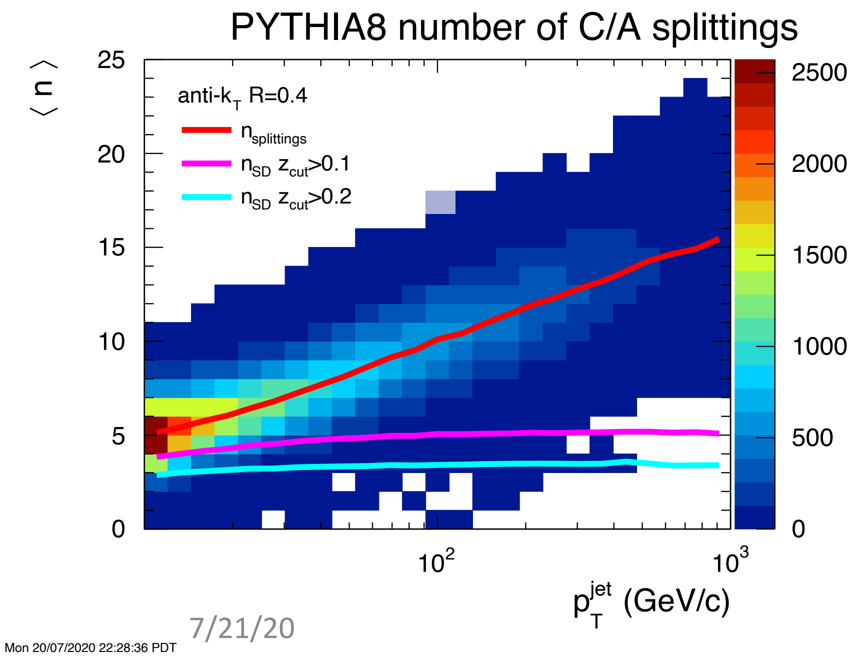


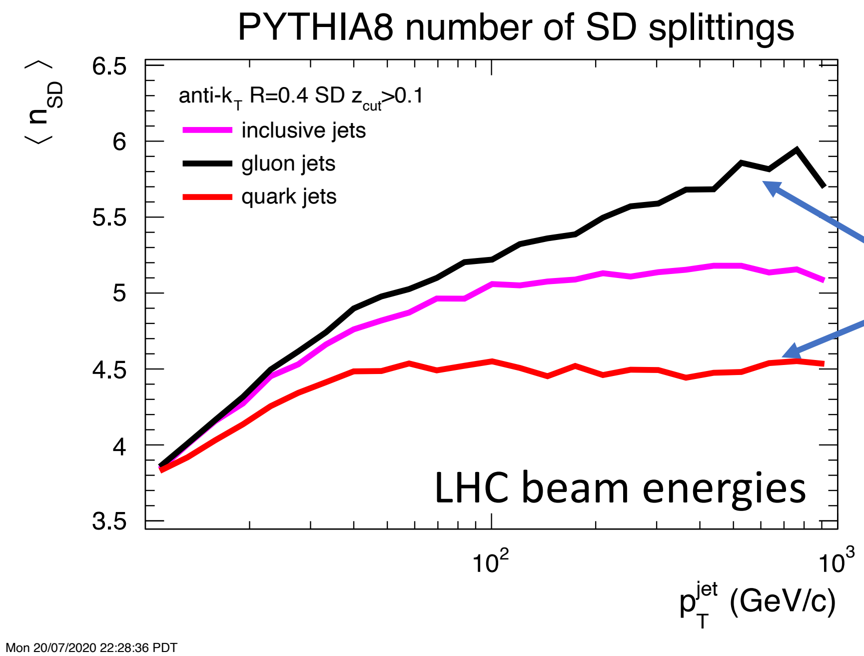
Purely MC exersize – compare LF to HF jets



Quark vs. gluon jets

Well known (but sometimes subtle points) – potential to leverage but also need to understand in AA collisions
⇒ Jet energy profile depends on energy – higher-E more collimated structure
  ⇒ Are lower pT jets more likely to be resolved by the medium?
⇒ Jet energy profile depends on parton type – glue induced jets less collimated than quarks
  ⇒ Do color factors – play a role – how strong? (showering dilutes the effect for incoherent interactions?)
⇒ Quark/gluon ration changes with jet pT
  ⇒ Higher momentum gluon jets appear as quark jets after the in-medium energy loss (softer prongs removed from the jet)



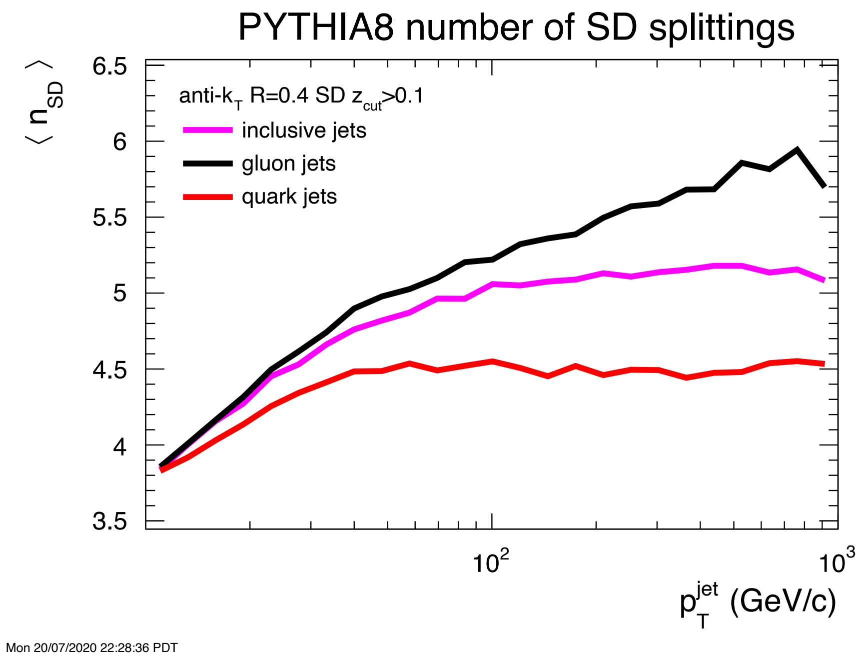


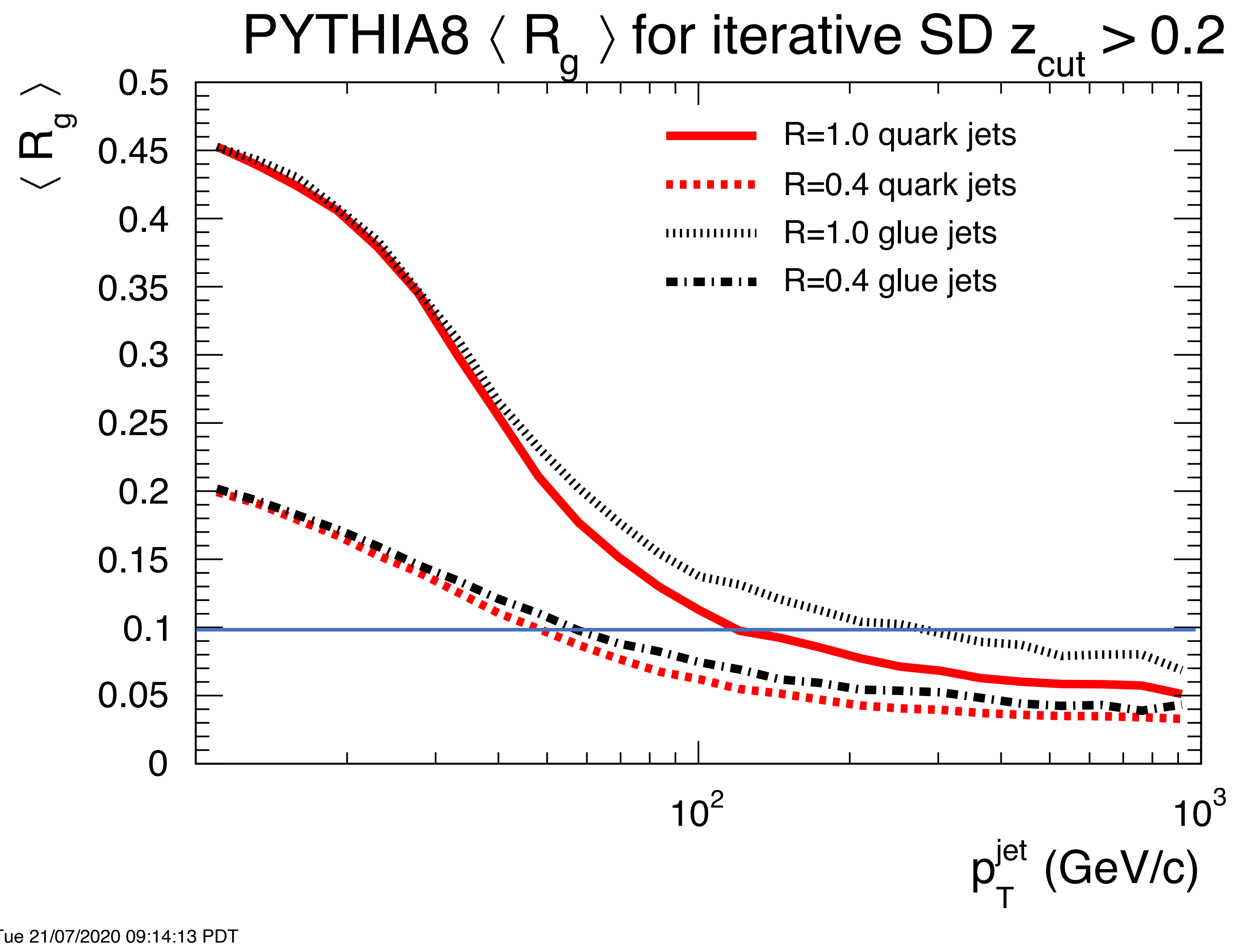
q/g:
- opportunity to leverage even at largest pT ('clean' splittings)
- leverage RHIC vs LHC – different q/g mix

Quark vs. gluon jets

q/g:
- opportunity to leverage even at largest pT (‘clean’ splittings)
- leverage RHIC vs LHC – different q/g mix

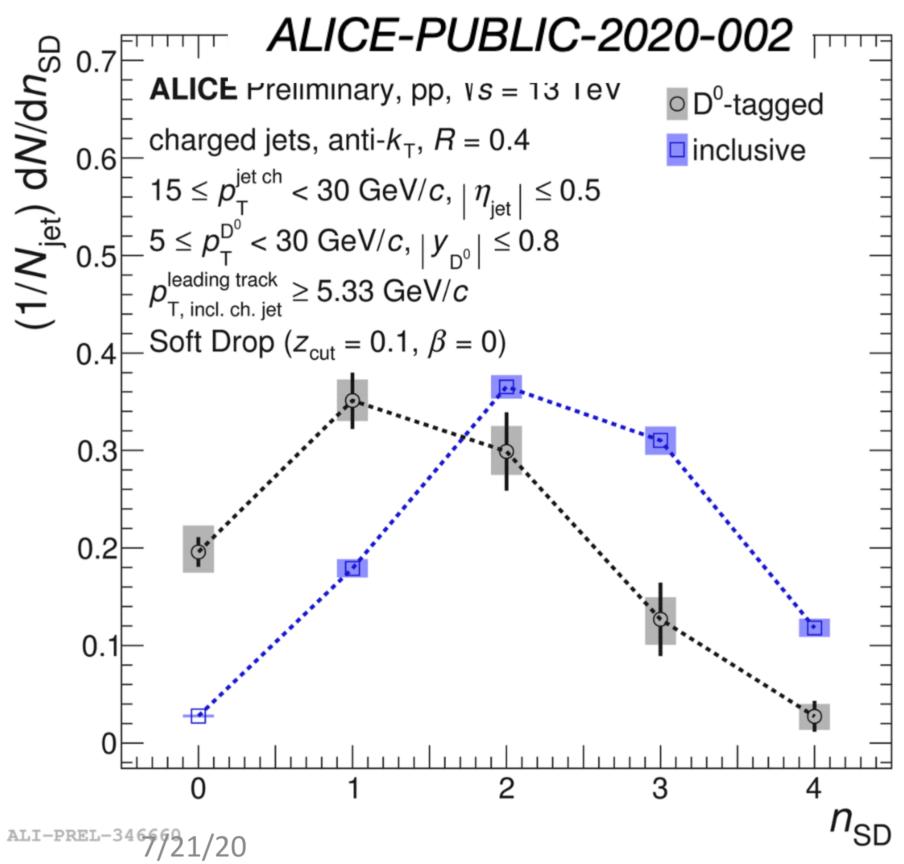
A warning: cutting on Rg may introduce even more complicated quark/gluon mixture





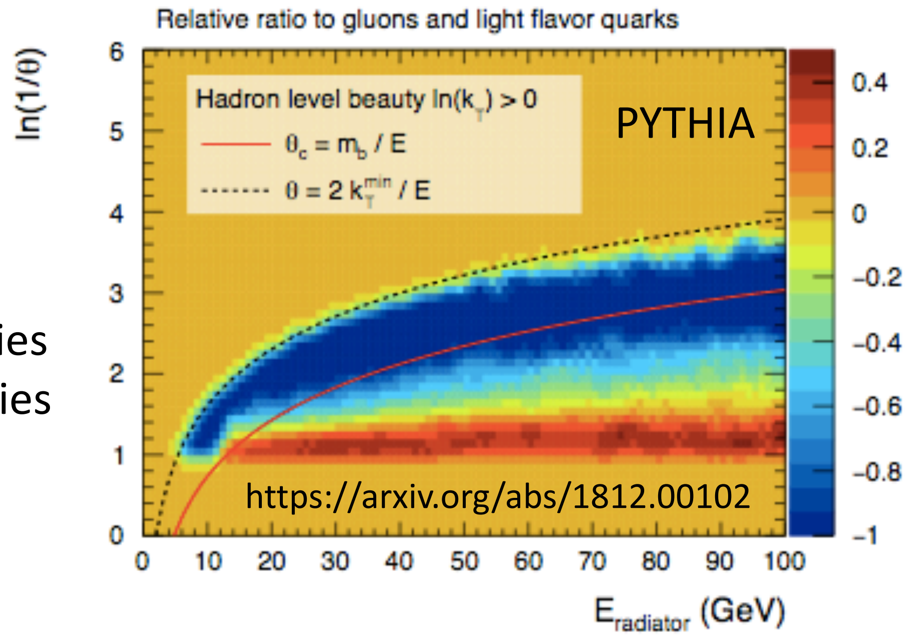
Quark vs. gluon jets

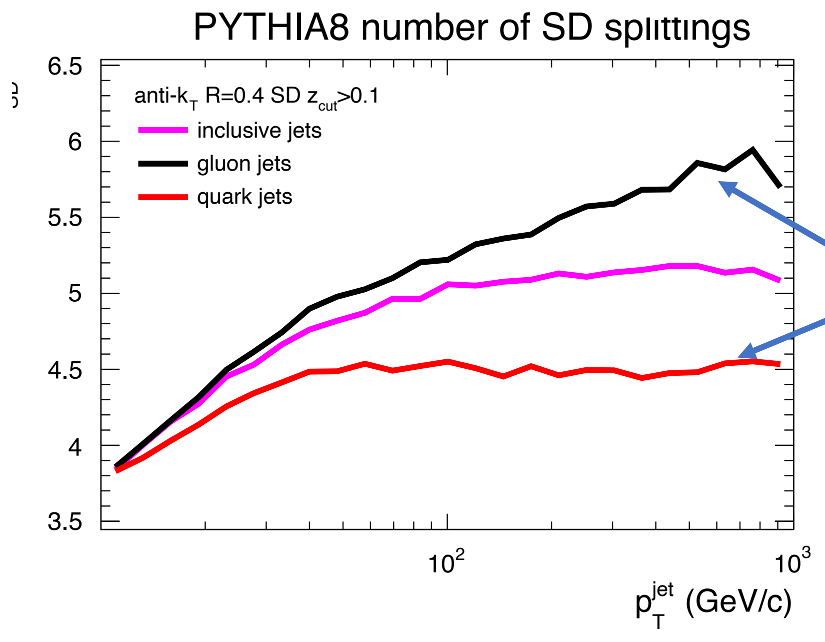
Recent measurement by ALICE
HF D-tagged jet nSD compared to inclusive



Quark mass matters for low-E jets: see also Dead Cone studies in pp - ALICE Preliminary studies with D-tagged jets

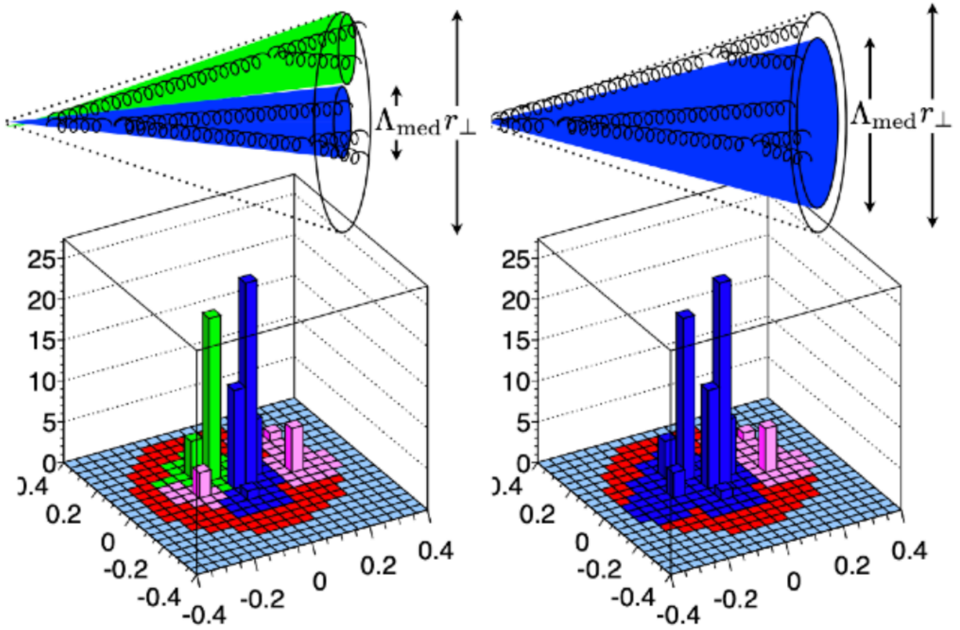
beauty



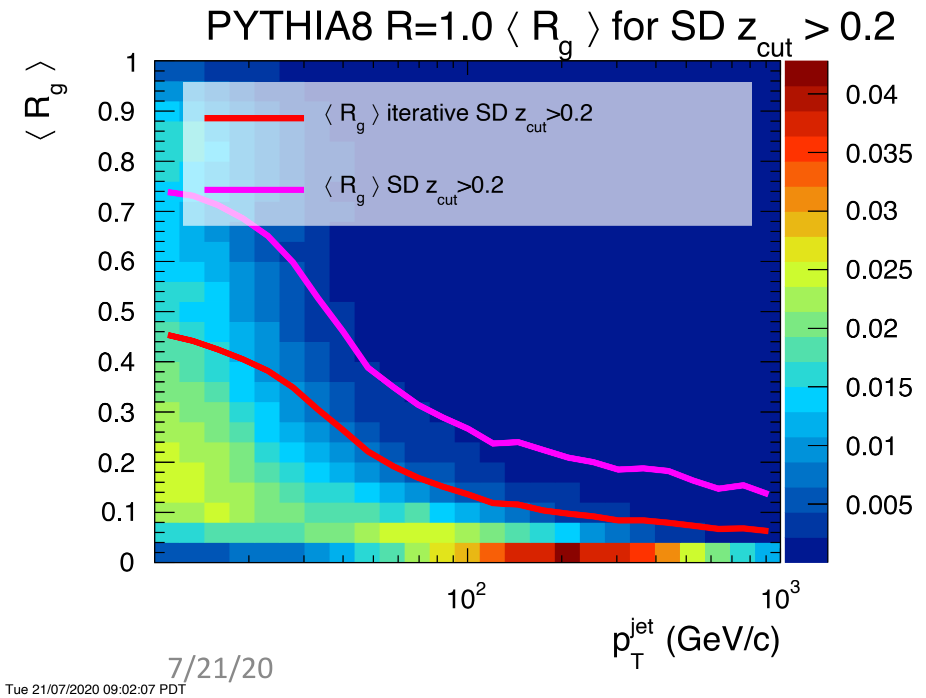


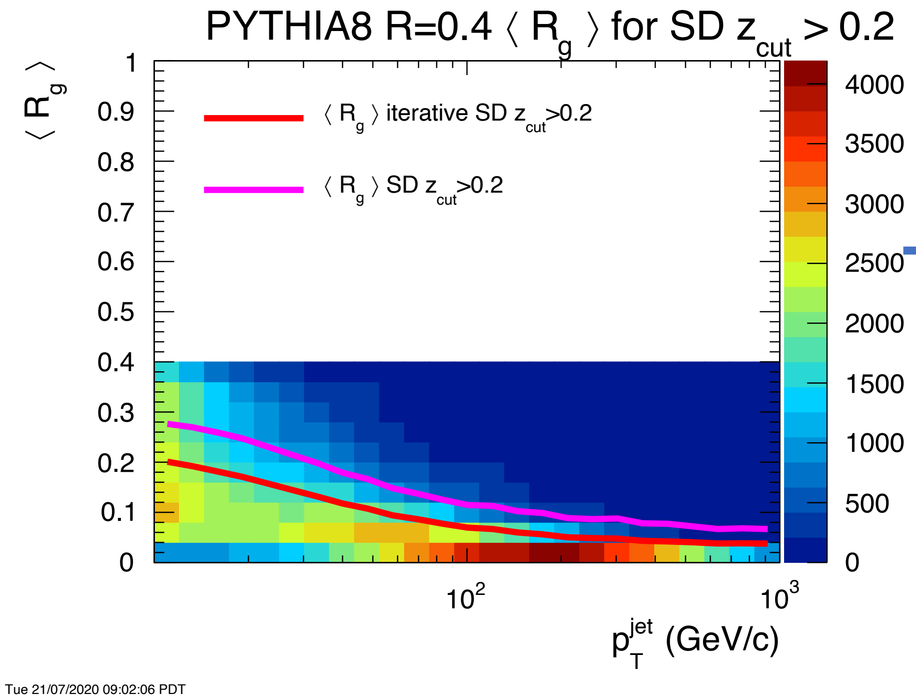
q/g:
- potential to leverage even at largest pT ('clean' splitings)
- leverage RHIC vs LHC – different q/g mix

Larger R jets
- more sensitivity to medium?



Mean Rg of hard (SD) splittings for jets with larger R
⇒ Larger sensitivity to medium properties / structure
⇒ Caveat: low-pT signal (prongs) closer to background scale
(more difficult experimentally? -> new tech. / mixed events?)



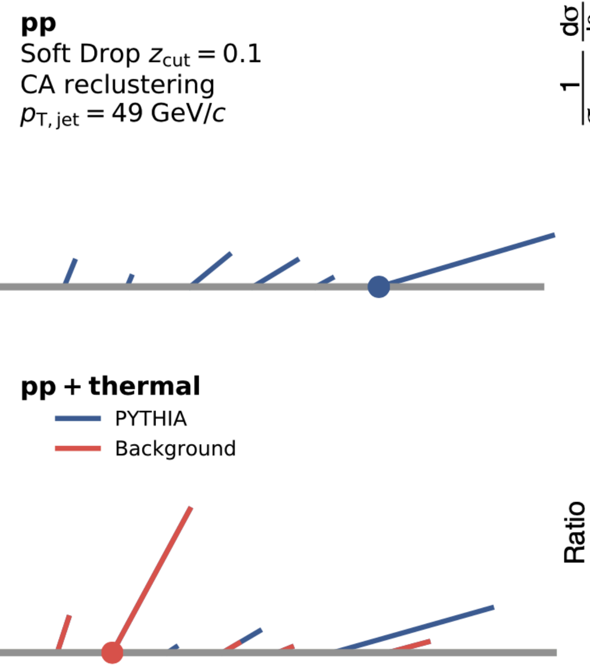


Direction to study:
- Larger R
- Access lower pT

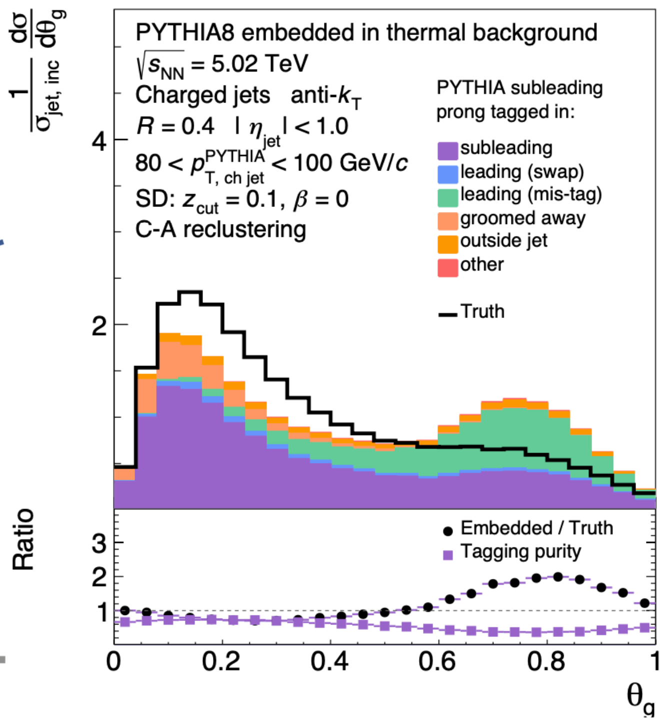
Beware of the background

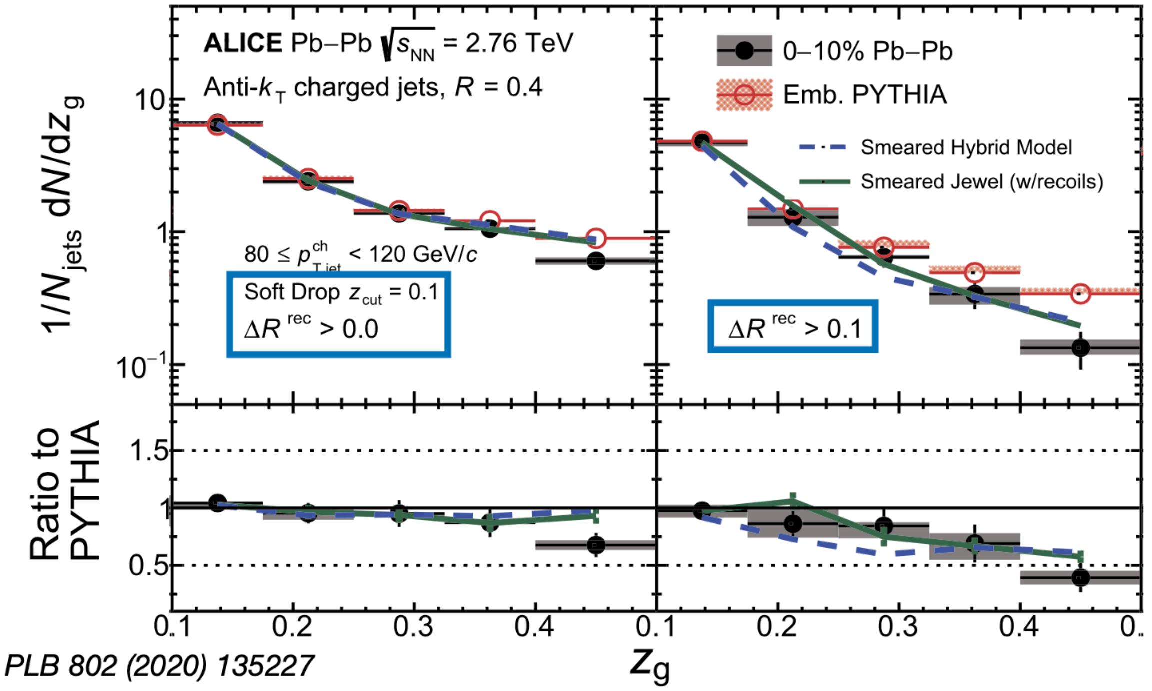
Slide by J. Mulligan

Embed PYTHIA into Pb-Pb background to estimate the fraction of subleading prongs in PYTHIA that are reconstructed in the subleading prong of the combined event



JM, M. Ploskon 2006.01812





PLB 802 (2020) 135227

Large number of misidentified Soft Drop splittings predominantly at large angle

Previous measurements with $z_{cut} = 0.1$ are significantly contaminated with background

New developments ongoing: use mixed events for more inclusive measurements – nSD for example

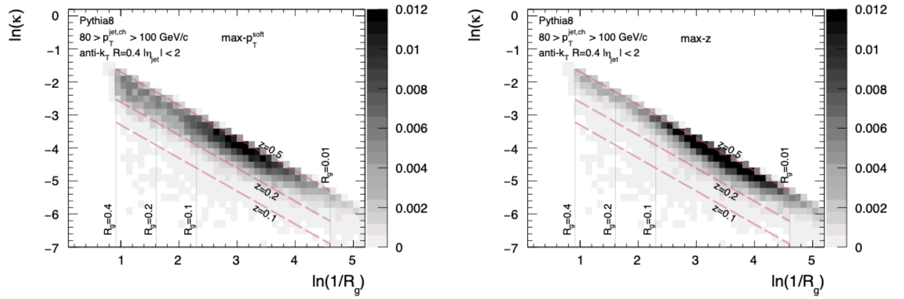
Explore with care…

Explore?
Different re-clustering algorithms
Different grooming algorithms
Different jet axis – and modifications of those in AA

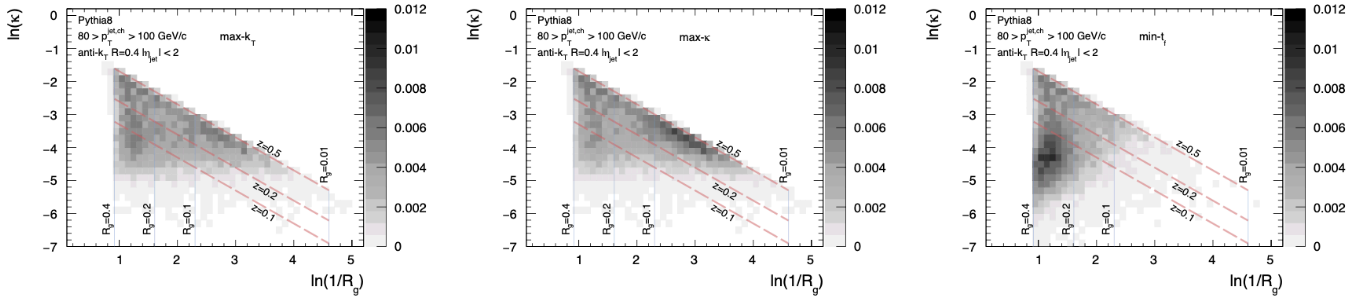
Novel approaches – 'dynamical grooming':

Y. Mehtar-Tani, A. Soto-Ontoso, K. Tywoniuk, Dynamical grooming of QCD jets, Phys. Rev. D 101 (2020) 034004. doi:10.1103/PhysRevD.101.034004.

https://arxiv.org/abs/2006.01812 – new/similar groomers

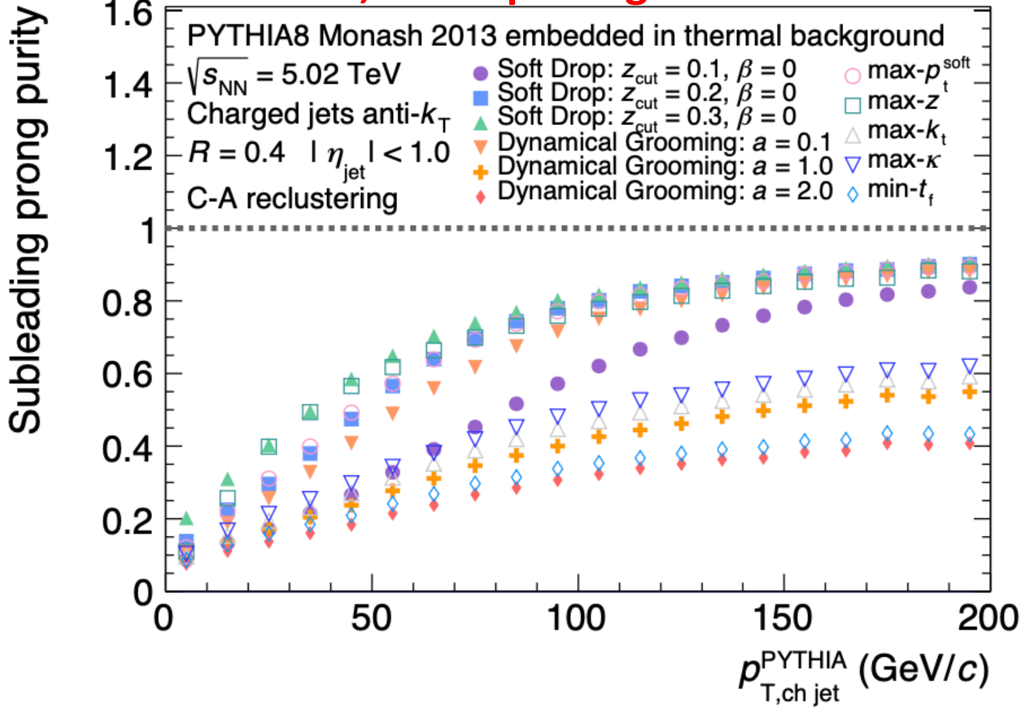


c) Primary Lund plane obtained with new groomers with the split selection depending on momentum of the prongs. Left: max-p_T^{soft}. Right: max-z.



d) Primary Lund plane obtained with new groomers with the split selection depending on momentum and the angle between the prongs. Left: max-k_T. Middle: max-κ. Right: min-t_f.

However, false splittings lurk…



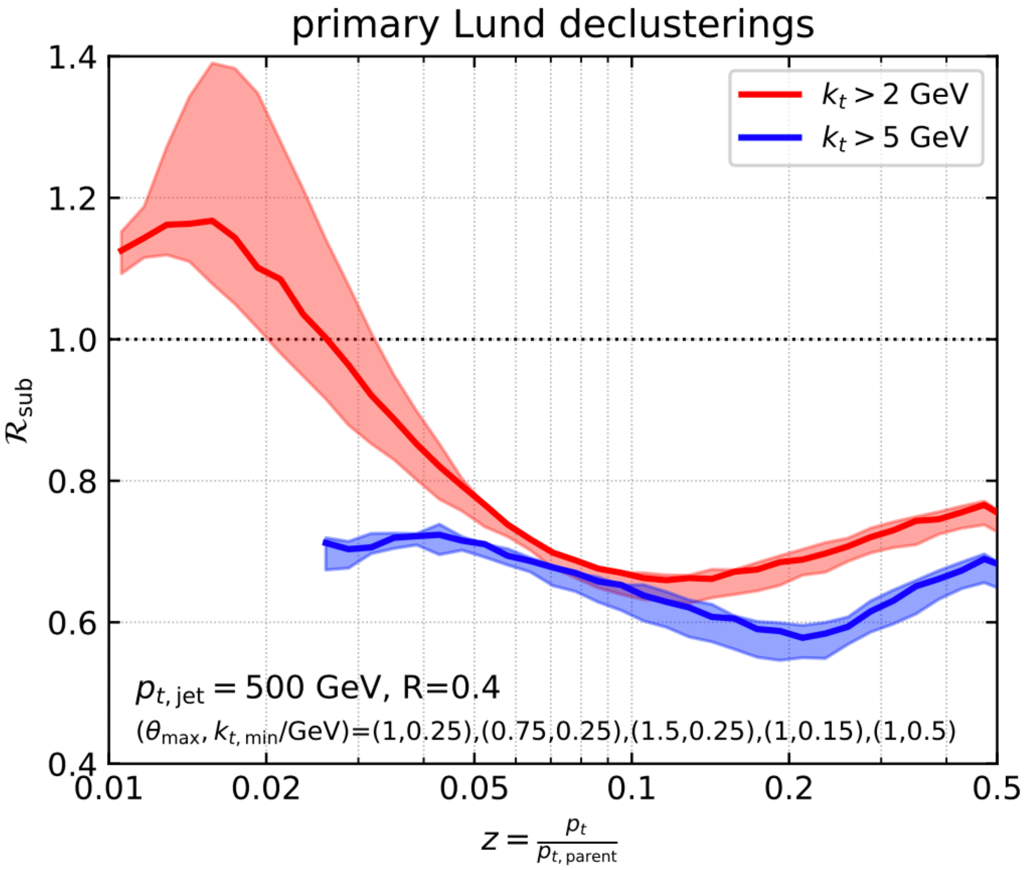
Not everything that's good in pp works well in PbPb (providing valid physics observables) – adopting needs a critical assessment

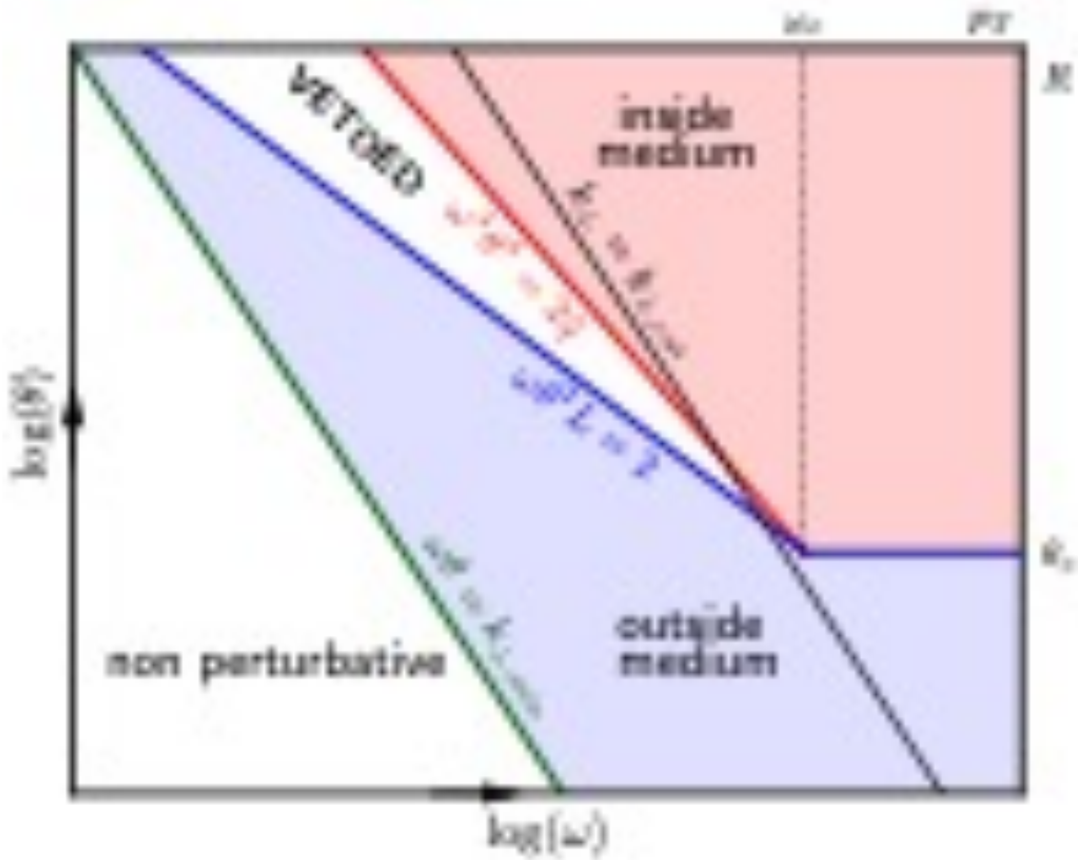
One new idea (the spirit of Lund Plane exploration)

Definition

$$\mathcal{D}_{\rm sub}(z) = \frac{1}{N_{\rm jets}} \frac{dN_{\rm sub}}{dz}$$

$dN_{\rm sub}$ number of **primary subjets** with $k_\perp > k_{\perp \rm cut}$ found after an iterative C/A declustering.



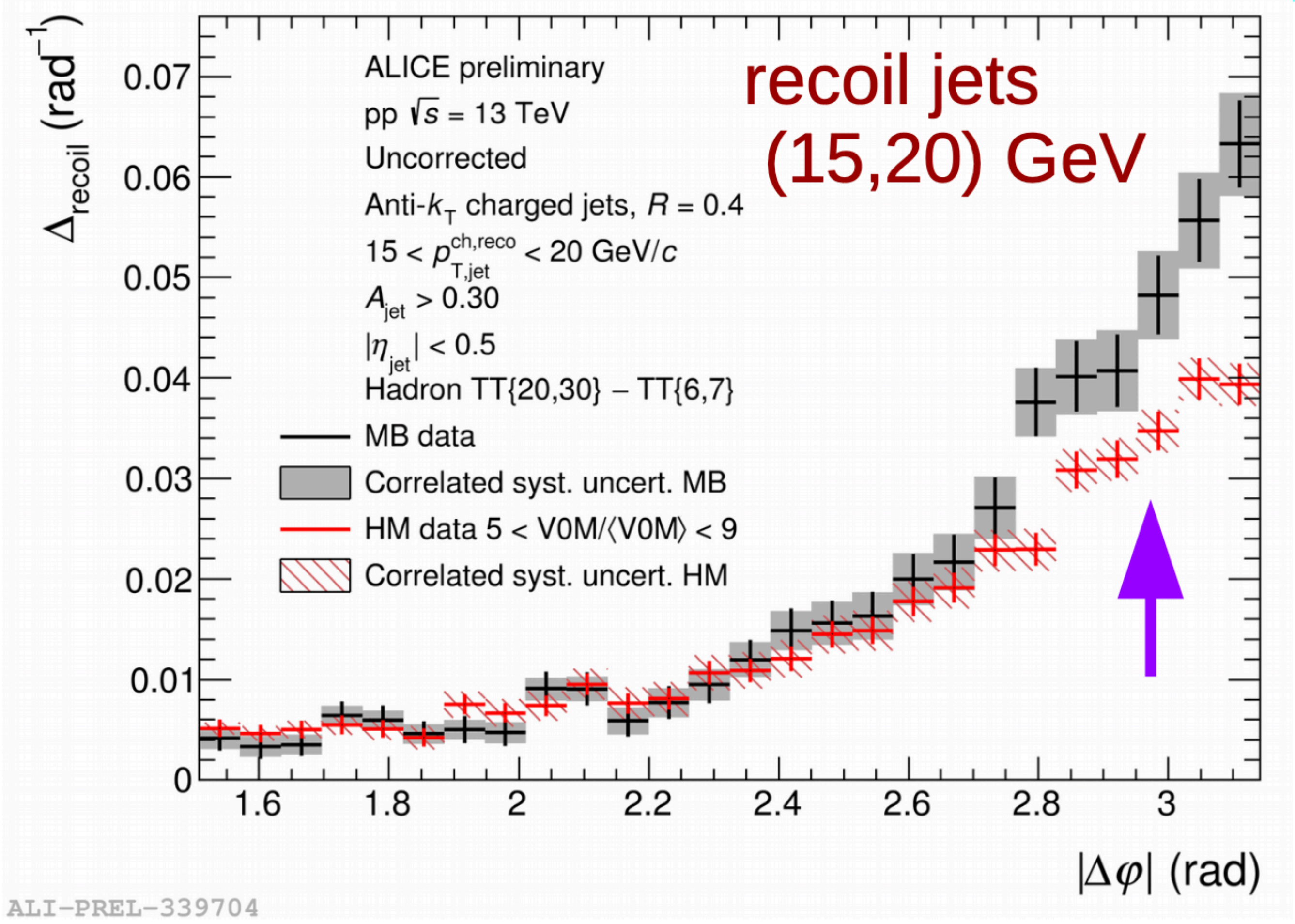


P. Caucal et al – Hard Probes 2020 - https://indico.cern.ch/event/751767/contributions/3771082/

High multiplicity pp

- Linear growth of HF as a function of mean multiplicity
- More multi-strange hadrons per pion – a continuous evolution from pp though pA to AA – note: dN/deta (pions) are a good approximation for entropy density
- RAA consistent with unity – no jet energy loss
  - Limits obtained from hadron-jet measurements Eloss < 400 MeV
- No modifications to jet composition (identified particles)
  - Better data needed?
- **Intriguing finding: hadron-jet angular distribution significantly different in HM as compared to Min Bias collisions**

HM pp – new measurements

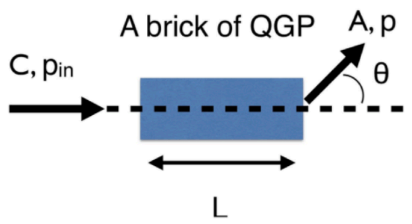


Very intriguing modification of azimuthal correlations of high-pT hadron and back-to-back jet in HM pp as compared to MinBias!

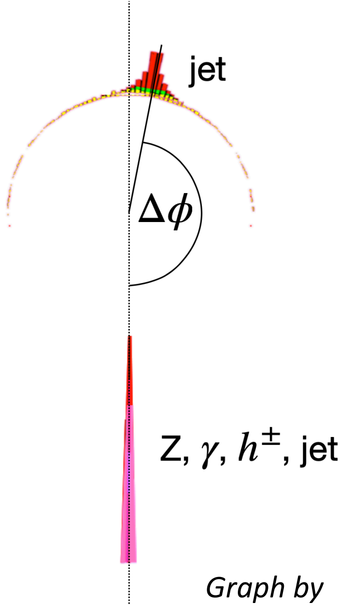
To add to the intrigue: PYTHIA shows similar effect

What's the connection to PbPb jet quenching?
=> This is **a similar** signal!

Francesco D'Eramo,[a,b] Krishna Rajagopal,[c] Yi Yin[c]



QGP in pp collisions ???
with inclusive RAA ~ 1



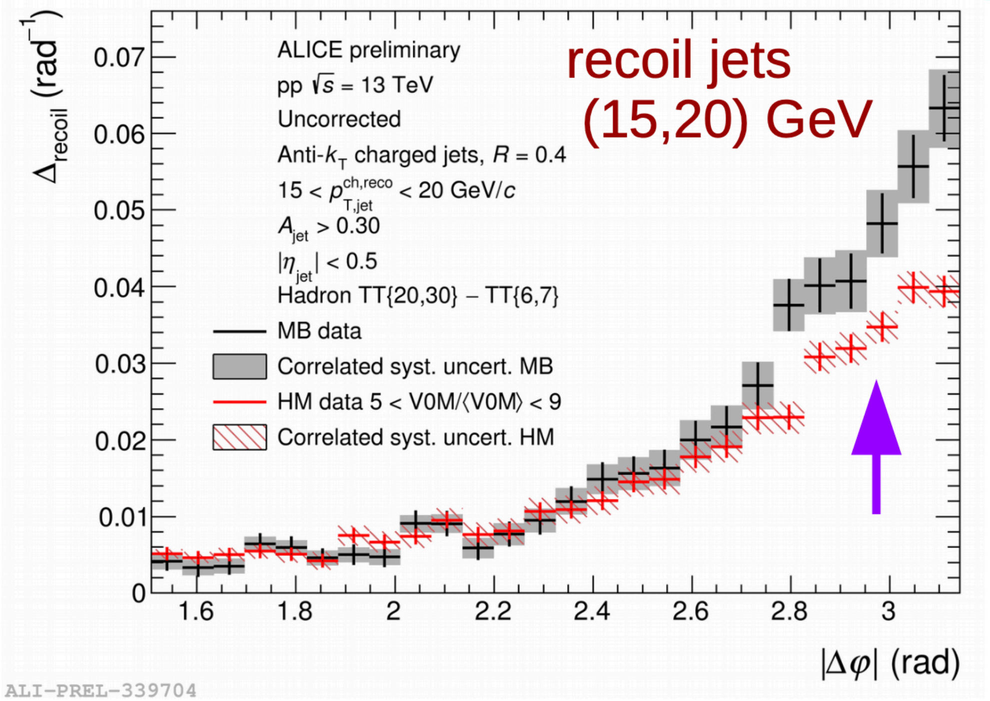
Graph by G. Roland

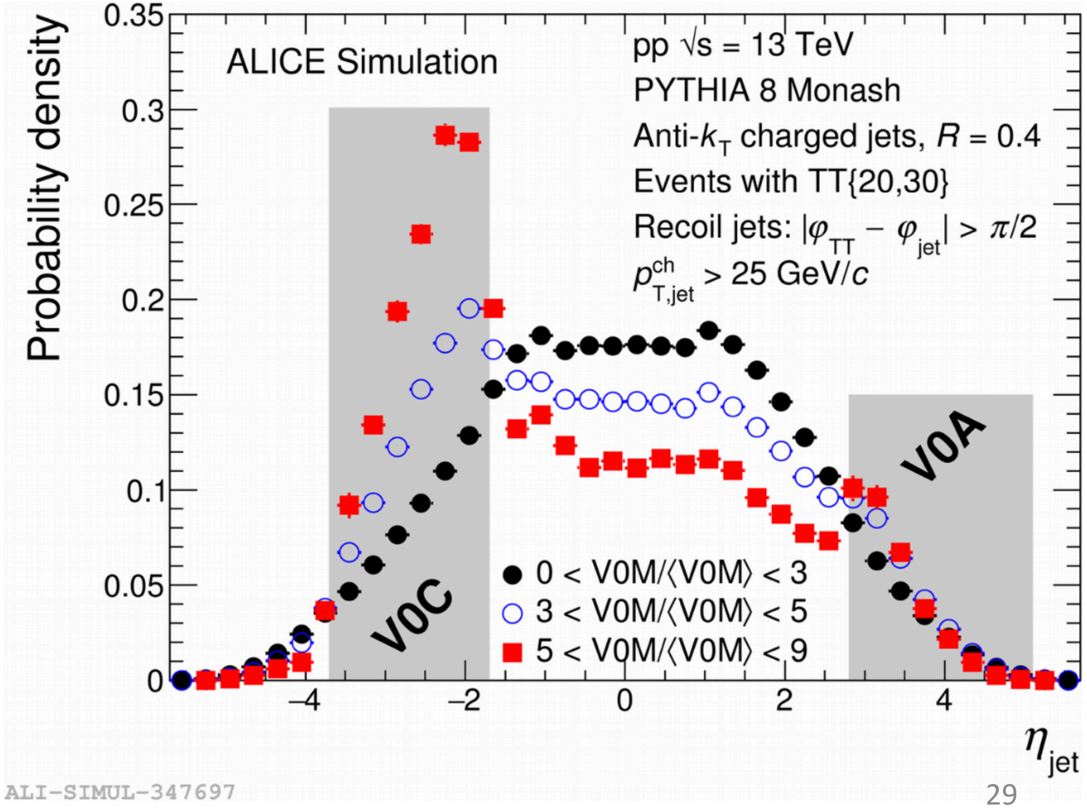
HM pp – new measurements

Very intriguing modification of azimuthal correlations of high-pT hadron and back-to-back jet in HM pp as compared to MinBias!

To add to the intrigue: PYTHIA shows similar effect

What's the connection to PbPb jet quenching?





Answer from simulations: forward-backward high multiplicity trigger selects predominantly events with large multi-jet configurations

⇒ Trigger induces a bias

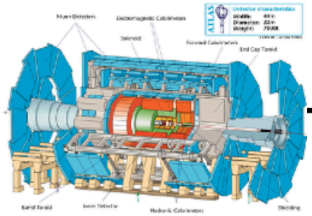
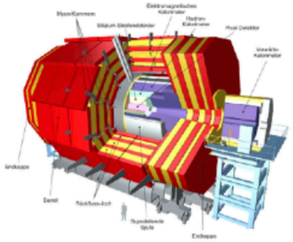
⇒ Asking for high multiplicity? – of course, nature provides!

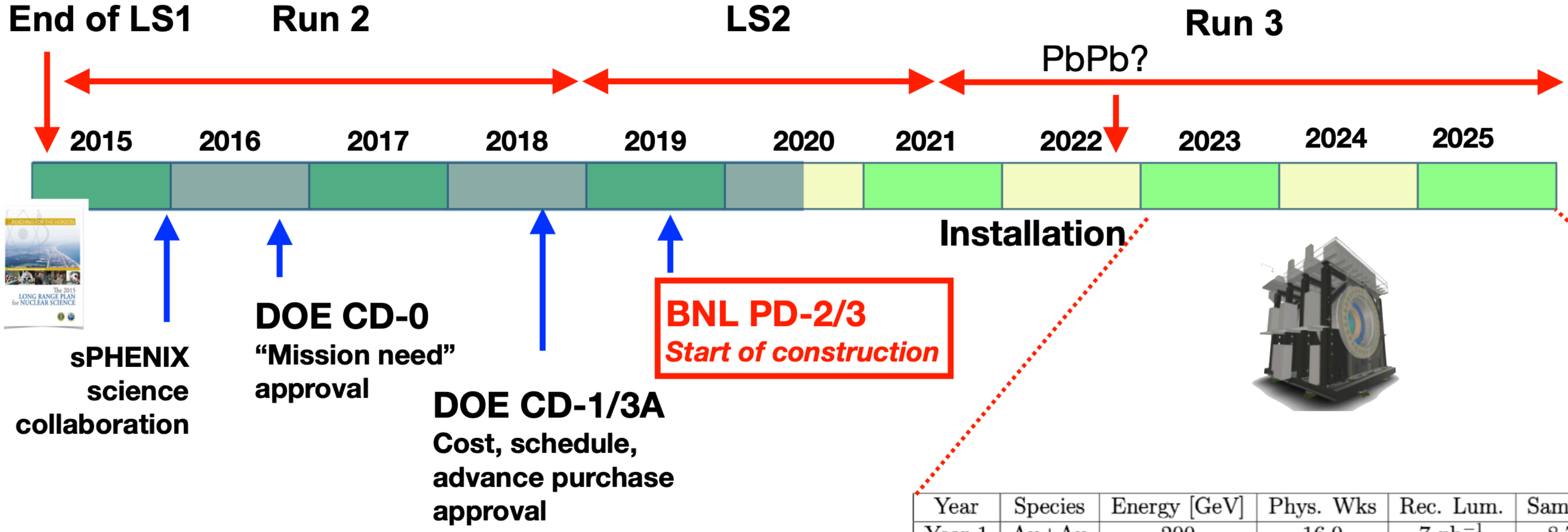
⇒ But what's the impact of this observation on the other "multiplicity'ology" findings…? – TBC

Next years of data – a recent compilation

Exciting future ahead

Slide by Gunther Roland at a recent workshop



Until 2029
ALICE: ~12/nb AA

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}

Executive Summary

- Need for precision measurements on jet substructure modifications that correlate the energy-loss and substructure modifications
  - Measure larger R – more sensitivity to medium resolution (experimentally difficult but ‘new’ methods may be available)
  - High **and low-pT** matters – dynamic range of the in-medium “radiators"
  - High precision Z-jet, gamma-jet, heavy-quark jets (at low pT) – towards q/g discrimination
  - New development: Inclusive measurements (all splittings – complete Lund Diagram) instead of groomed -> ensemble basis analyses (subtract the mis-tagged splittings)
  - Expand on novel Machine Learning techniques – suppress / improve corrections (background)
- High multiplicity collisions are not lower multiplicity PbPb collisions
  - HM pp as a good reference for (likely only) $N^{x}LO$ corrections to in-medium effects (within jets) in AA => good lesson for what high multiplicity pp collisions are
- Looking forward to the LHC Run-3&4 and RHIC sPHENIX era
- Beyond that? Yoctosecond structure of QGP with top quarks – HE-LHC (low signal for HL-LHC) (https://doi.org/10.1016/j.nuclphysa.2018.11.014)

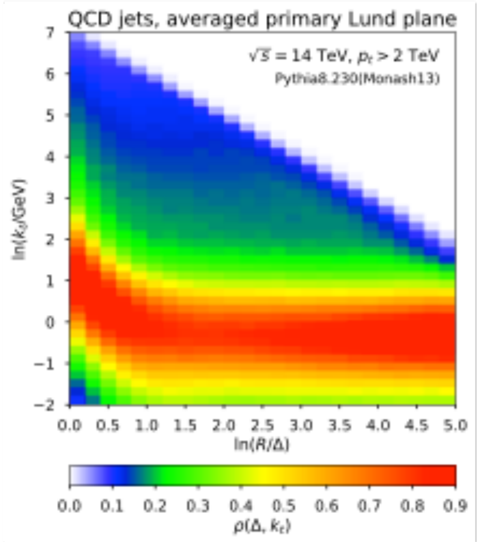
backup

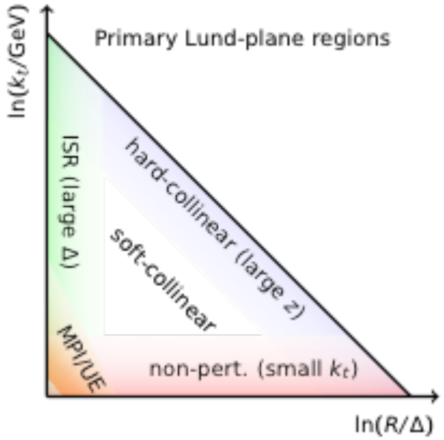
Jet Lund diagram

$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

- Comparison of event generators
- Use for ML – jet ID (RHS below: boosted electroweak boson tagging at high momenta)





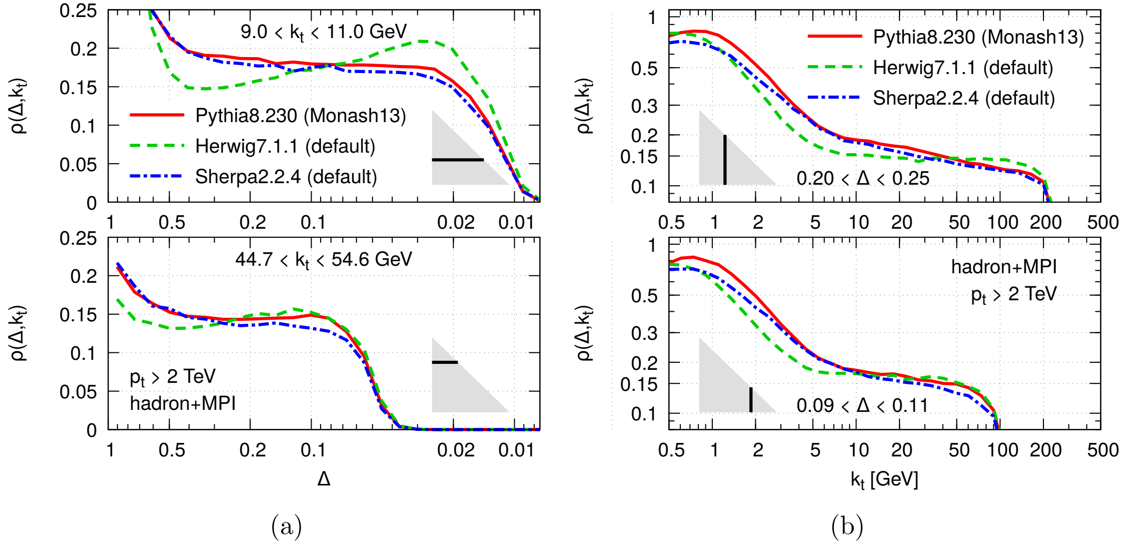
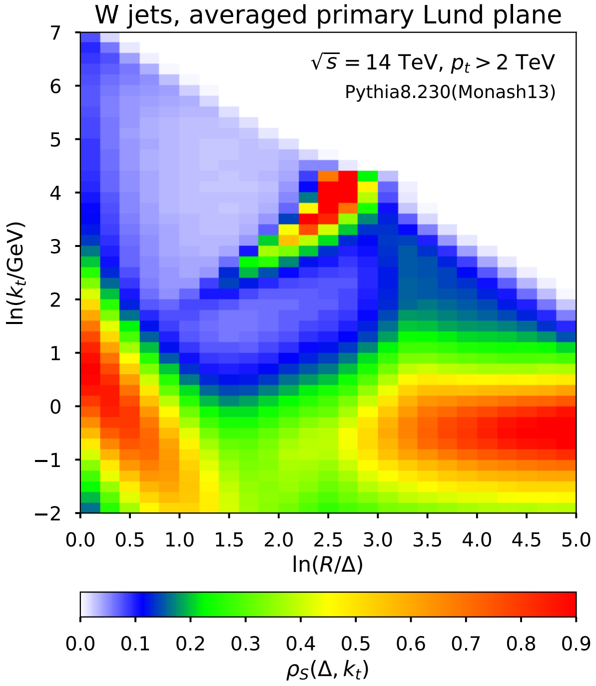


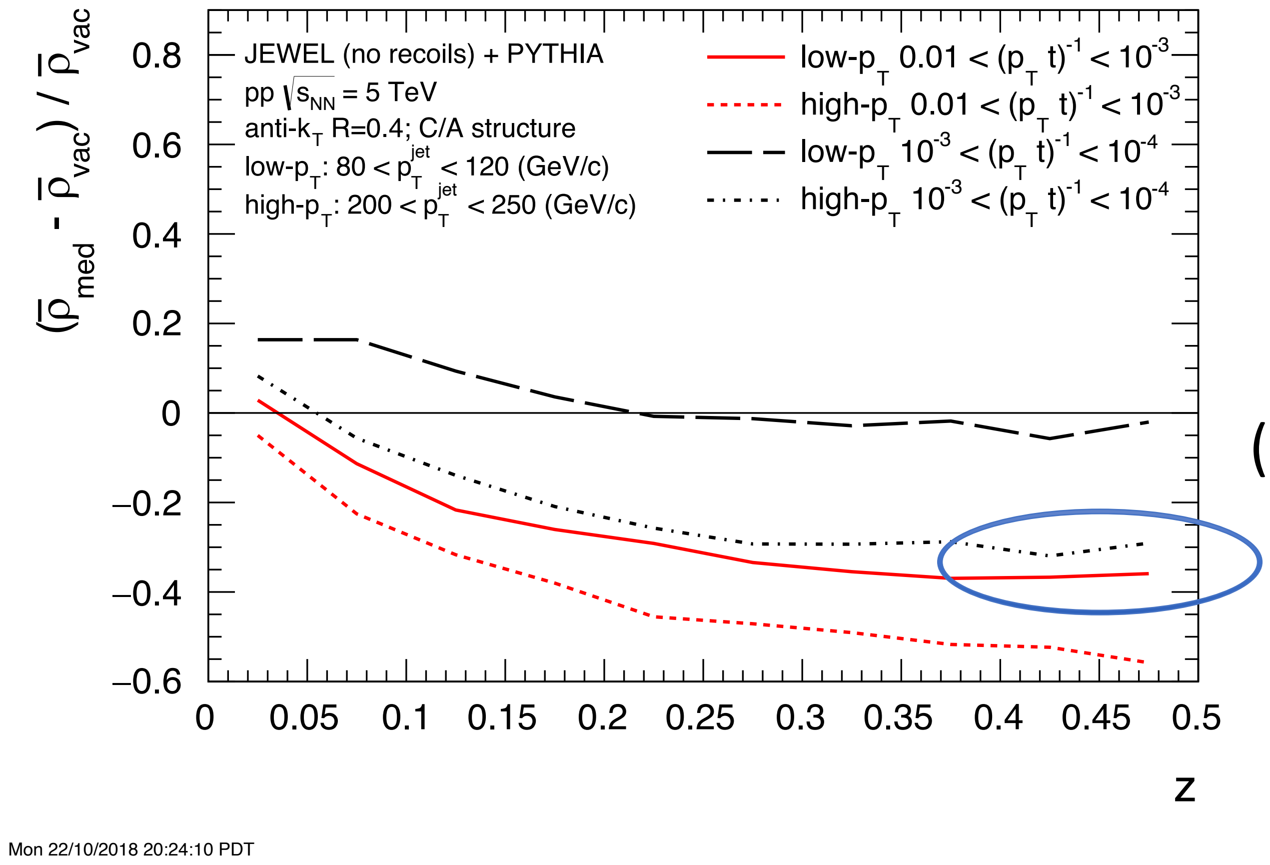
Figure 3: Emission density along slices of the Lund plane, at fixed k_t (top) and Δ (bottom), comparing three event generators.



Jet Lund diagram slicing through time

$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$



Low- with high-p_T for the similar t

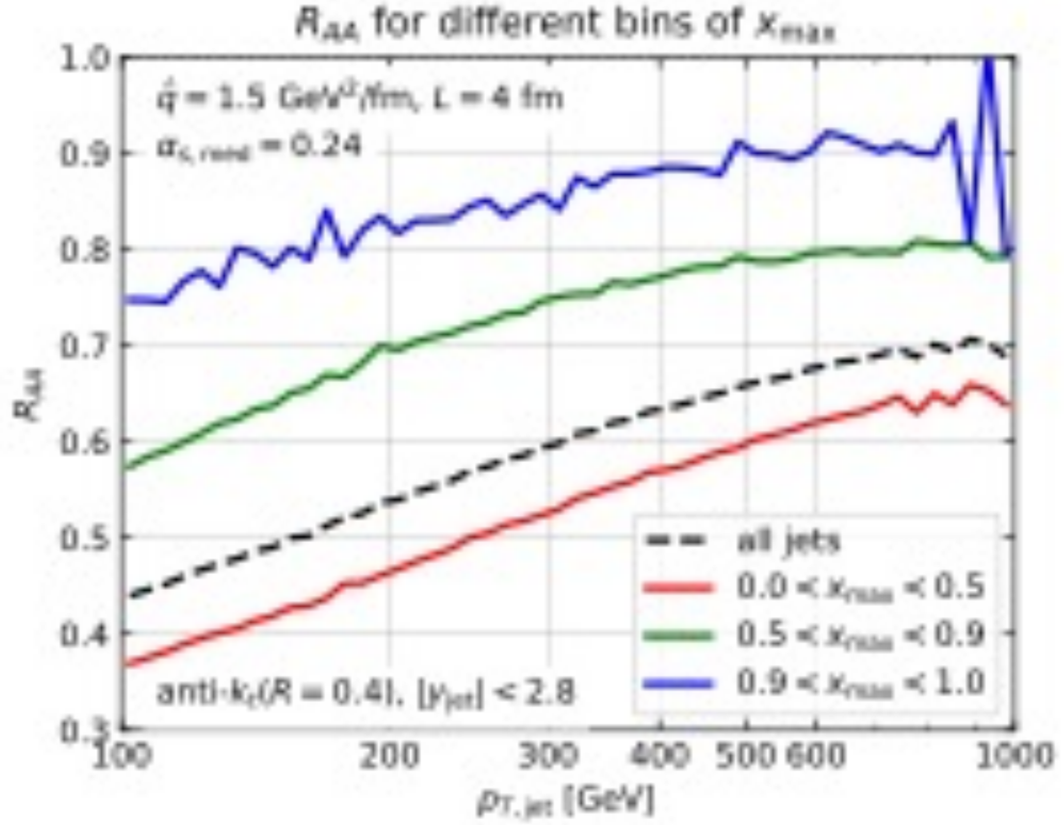
⇔

similar suppression (scaling factor for p_T x t roughly 80/200)

Large-x behaviour: bias towards "hard-branching" jets

- Not a nuclear change in the fragmentation pattern, but in the statistics of hard-fragmenting jets.
- Hard-fragmenting jets have less structure, hence they lose less energy.
- Additionally: bias towards quark-initiated jets.

see also Casalderrey-Solana et al.(1808.07386) 2019, Spousta and Cole, (1504.05169) 2016



PC, Iancu, Mueller, Soyez (2005.05852), 2020

P. Caucal et al – Hard Probes 2020 - https://indico.cern.ch/event/751767/contributions/3771082/